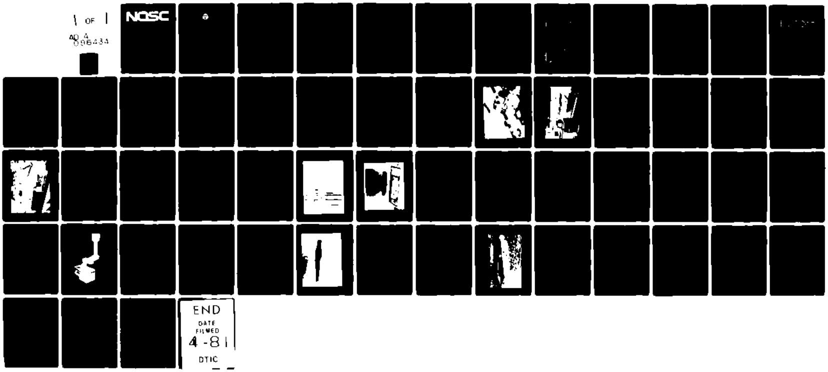
AD-A096 434 NAVAL OCEAN SYSTEMS CENTER SAN DIEGO CA F/G 13/10.1
FREE-SWIMMING SUBMERSIBLE TESTBED (EAVE WEST).(U)
SEP 80 P J HECKMAN
UNCLASSIFIED NOSC/TR-622 NL



LEVEL II

NOSC

NOSC TR 622

NOSC TR 622

AD A096434

Technical Report 622

FREE-SWIMMING SUBMERSIBLE TESTBED (EAVE WEST)

Paul J. Heckman, Jr.

15 September 1980

Interim Report

Prepared for
Research and Development Program
Outer Continental Shelf Oil and Gas Operations
US Geological Survey

FILE COPY

Approved for public release; distribution unlimited

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

SL GUILLE, CAPT, USN
Commander

HL BLOOD
Technical Director

ADMINISTRATIVE INFORMATION

This effort has been completed by the Ocean Technology Department of the Naval Ocean Systems Center in cooperation with the U.S. Department of the interior, Geological Survey, Reston, Virginia. This work was funded by Mr. John Gregory of the U.S. Geological Survey under program element FG0V, work unit number 521-MS31. It is part of a total research-and-development program designed to supply the technology required for pollution prevention and safety in outer continental shelf oil and gas operations. Unmanned, untethered submersible systems have a significant potential for upgrading the scope and complexity of these inspection missions in a cost-effective manner. The investigation of unmanned submersibles for pipeline and structure inspection represents an attempt to transfer technology from the Navy's Ocean Technology Program for use in these inspection missions. The Navy, in turn, will be able to adapt the untethered vehicle techniques to search and recovery operations at sea.

Released by
I.P. Lemaire, Head
Advanced Systems Division

Under Authority of
H.R. Talkington, Head
Ocean Technology Department

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NOSC Technical Report 622 (TR 622)	2. GOVT ACCESSION NO. AD-A096 434	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FREE-SWIMMING SUBMERSIBLE TESTBED (EAVE WEST)		5. TYPE OF REPORT & PERIOD COVERED Interim Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Paul J. Heckman, Jr		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Systems Center San Diego, CA 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS FGOV, S21-MS31
11. CONTROLLING OFFICE NAME AND ADDRESS US Geological Survey Reston, Virginia		12. REPORT DATE 15 September 1980
		13. NUMBER OF PAGES 54
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Submersibles
Tethering
Underwater Tools
Underwater Vehicles

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report discusses the technology required to develop unmanned free-swimming submersibles to be used for inspecting undersea pipelines and structures. Of particular concern is the use of solid-state electronics and microprocessor technology. The philosophies concerning performance criteria, design flexibility, man/machine interface, and cost are discussed, and the vehicle's performance in these areas is evaluated.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE*(When Data Entered)*

SUMMARY

PROBLEM

Develop technology for conducting underwater inspection by means of unmanned, free-swimming submersibles to provide a potentially cost-effective means of inspecting undersea pipelines and structures. Underwater pipeline and structural inspection tasks are of direct concern to the U.S. Geological Survey's (USGS's) research-and-development program, whose major objective is to develop technology for pollution prevention and safety for outer continental shelf oil and gas operations.

RESULTS

A technology transfer program was established to transfer the Navy's unmanned, tethered vehicle technology experience to the application of undersea pipeline and structure inspection and to explore advanced concepts in unmanned, untethered vehicle design technology. An unmanned, free-swimming testbed submersible was designed and developed to act both as a testbed for new technological concepts in underwater inspection and as a means of verifying these concepts by demonstration on an operational platform. The resulting vehicle (EAVE WEST) has proven to be feasible, flexible, and adaptable to a variety of concepts and technologies applicable to both USGS and Navy requirements.

RECOMMENDATIONS

1. Adapt a wide variety of artificial intelligence concepts for use in the vehicle, and test and evaluate these concepts for both Navy and USGS applications.

2. Use the vehicle as a testbed for advanced man-machine interface concepts for undersea inspection and work applications.

CONTENTS

INTRODUCTION

During the past decade, there has been a vast amount of undersea drilling for tapping oil and natural gas reserves; for example, more than 3000 structures were erected in the Gulf of Mexico alone within the last 10 years (reference 1). The requirement for underwater inspection of these structures and their pipelines is a growing concern. The cost of inspection is high, and it is expected to increase as drilling platforms move into deeper and more hostile waters and the complexity of the structure increases.

The diver is presently the primary means of inspecting these structures; his/her primary tools are visual inspection, photography, and television documentation. Although manned submersibles and tethered, unmanned submersibles are being used, there are problems concerning their use, e.g., entanglement and ship-support costs. The availability of relatively inexpensive, free-swimming (tetherless) robot vehicles may make routine underwater inspections and surveys for many pipelines and structures both economically feasible and practical. Although the free-swimming robot submersible may never truly replace the tethered submersible, just as the manned submersible has never truly replaced the diver, there are applications in which the vehicle has its advantages.

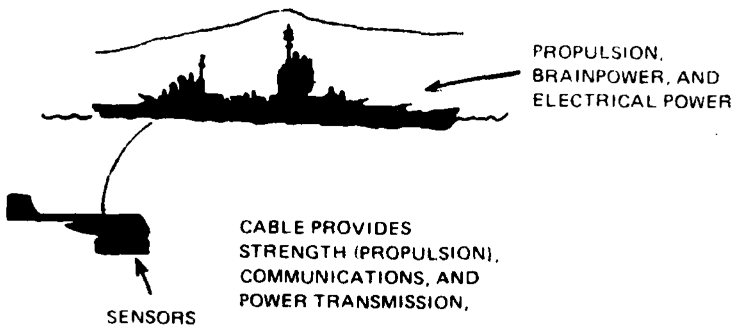
BACKGROUND

There are three ways to extend the capability of the human being to perform work in a hostile environment (reference 2). They are protection, projection, and replacement.

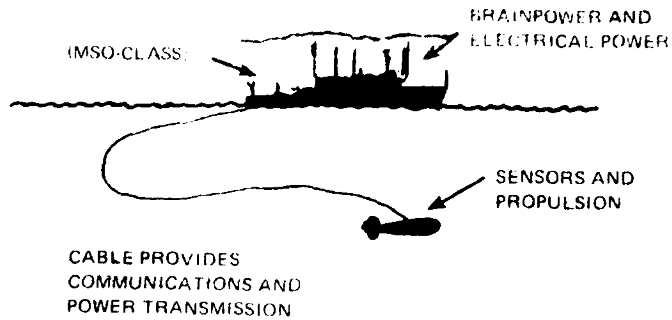
Protection refers to enclosing man in a protective environment while allowing him reasonable access to the desired environment through sensors and effectors, e.g., diving suits, one-atmospheric diving chambers, and manned submersibles. Projection involves placing the sensors and effectors in a remote hostile environment while locating man in a nonhostile environment, e.g., towed, tethered, and acoustically controlled underwater vehicles and teleoperators. Replacement, the most sophisticated means of dealing with a hostile environment, involves replacement of both mind and body by another entity designed to accomplish the desired task, e.g., free-swimming autonomous vehicles. Thus, the human accomplishes tasks in hostile environment by protecting himself against the environment, using long arms with remote sensors, or devising a machine to perform the task by itself.

In the ocean environment the use of projection and replacement systems, rather than protection devices, can be justified in terms of danger to human life, payload cost of carrying life-support systems, and additional operating costs. Although there have been arguments for several years over the use of divers, manned vehicles, and unmanned vehicles (references 3, 4 and 5), it is safe to predict that all three will continue in use, each with its specific application.

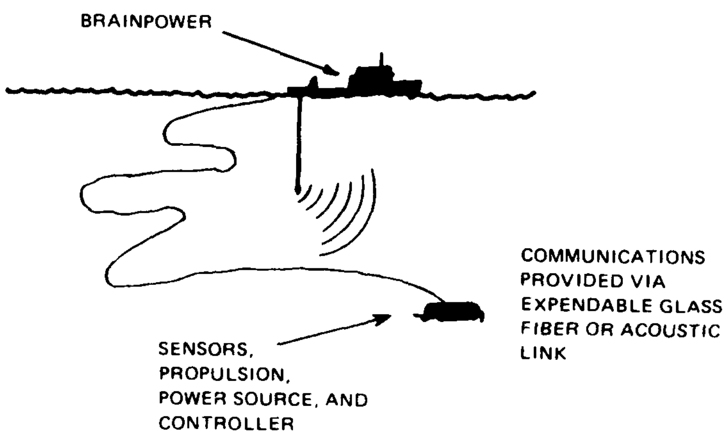
The overall trend of unmanned vehicle systems toward autonomous operation can be seen in figure 1, which shows four generally accepted classifications of unmanned underwater vehicle systems. Towed vehicle systems (figure 1A) are operated by means of an umbilical cable which supplies mechanical propulsion,



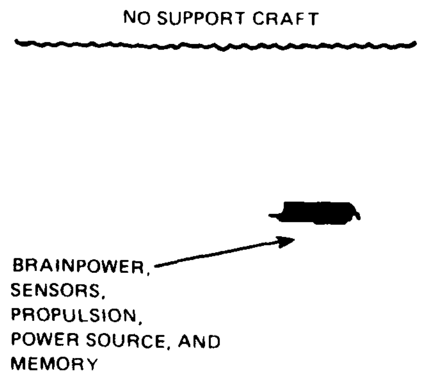
Part A. Towed vehicle.



Part B. Tethered vehicle.



Part C. Supervisory-controlled vehicle (free swimmer).



Part D. Totally autonomous vehicle (free swimmer).

Figure 1. Classification of undersea, unmanned vehicle systems.

electrical power, and communications to the vehicle from a rather large surface support craft. The submersible is rather uncomplicated in nature, but its maneuverability is poor. The tethered vehicle incorporates an umbilical cable which provides electrical power and communications (figure 1B). Because the cable no longer supplies mechanical power to the vehicle, the cable is lighter and more flexible and the support ship's size requirements are reduced. Maneuverability of the vehicle is such that undersea inspections and work operations are possible. The recent appearance of the free-swimming unmanned submersible has been made possible because of advances in LSI technology and the development of microcomputers. In this case, the approach to the extension of man in the underwater environment actually crosses the line between projection and replacement. Figure 1C shows a supervisory-controlled, free-swimming vehicle. Because this configuration requires only a communication link to the surface support ship, the vehicle has many of the tethered vehicle's advantages of maneuverability for inspection and limited work missions without the problems associated with a tether. Eliminating the tether offers the vehicle the performance advantages of (1) higher speeds due to the reduction of cable drag and (2) entanglement-free operations around structures. Note that because the tether is eliminated, there is no need for shipboard storage of the cable during transit, for a cable-handling system and its associated manpower requirements, or for station keeping during an operation at sea. Thus, the support ship requirements are again diminished with respect to size and, consequently, operating costs. If the communication requirements for the free swimmer are reduced to zero, a totally autonomous submersible can be produced (figure 1D). The support ship is then eliminated, and the approach to underwater operations becomes that of replacement. All the brainpower, sensors, effectors, propulsion, and power source requirements for performing a given operation are contained within the vehicle itself. It is thus possible for a single vehicle to incorporate both projection and replacement modes of operation depending upon the task undertaken.

Based on the above discussion, the terms free-swimming or untethered, unmanned submersible do not necessarily refer to autonomous vehicles. Conversely, one cannot imply that a free-swimming unmanned submersible is impractical, if there is no direct method of communicating with it during a given operation. Certain totally autonomous operations are practical even with today's technology. This has become increasingly evident as the development of the testbed free-swimming submersible described in this report has progressed.

For the past several years, the Naval Ocean Systems Center (NOSC) has been involved with the development of small, unmanned vehicle systems. The list of these submersibles includes the first hydraulic Snoopy, the Submerged Cable-Actuated Teleoperator (SCAT), Electric Snoopy, NAVFAC Snoopy, and the Mine Neutralization Vehicle (MNV). The development of control for these vehicles has progressed from being completely manual using hardwire cable to having some automatic control circuits directed by a lightweight, low-drag cable with multiplexed data and control signals. The general trend of tethered vehicle design is toward more autonomous control (see table 1). The microprocessor has allowed simplification of the hardware required for small unmanned vehicles, i.e., the designer has replaced much of the hardware control with flexible software allowing the vehicle considerable flexibility in meeting changing mission requirements.

Subsystem	1957 (Beginning of Development) First Unmanned Vehicle Design	1967 Present Designs	1977 Free-Swimmer Design	1987 Robot Vehicles with Artificial Intelligence
Electronic design base	All analog circuitry	Hardwire digital with analog feedback control	Microprocessor-based digital using A/D and D/A interfaces with sensors and controls	Distributed microprocessor architecture
Control	Joystick control with television feedback	Analog circuit feedback control loops to provide auto-hold functions	Digital circuit feedback control to provide auto-hold functions and programmable track	Scene analysis Pattern recognition Obstacle avoidance Onboard absolute (transponder) navigation and/or inertial navigation
			Automatic emergency routines	Adaptive control system Self preservation Self-organizing system
Display console	Special hardwire console rack	Special hardwire consoles with sonar systems added	Alphanumeric CRT display and eventually a graphics system augmented with joystick	Alphanumeric and color graphics display systems augmented with joystick
Data storage	None on vehicle Television recording on surface	Film recording on vehicle Television recording with voice, time, etc. on surface	Film recording on vehicle Television frame grabbing SLS recording	More data storage through bubble memories and disk recording
Support equipment (required)	Support craft Control console Vehicle-handling system Multiconductor cable Cable-handling system	Support craft Control console Vehicle-handling system Coaxial cable and multiplex Minimum cable-handling system	Support craft Control console Vehicle-handling system	Support craft Control console Vehicle-handling system
Sensor systems	Television camera	Television camera Film camera Sonar	Television Film Side-looking sonar Magnetometer	Additional sensors

Table 1. Progress of Unmanned Vehicle Technology.

PROGRAM OBJECTIVES

The purpose of the free-swimming vehicle development effort described in this report is to use new technological advances in solid-state electronics and microprocessor technology to accomplish the following:

1. Investigate the use of supervisory-controlled and autonomously controlled unmanned submersibles for undersea pipeline and structure inspection.

2. Test and demonstrate advanced concepts in underwater submersible design on an actual underwater platform.

NOSC is interested both in transferring its technology to the underwater offshore oil community and in developing undersea, unmanned vehicle technology for use in Navy applications. The effort described herein was performed under the sponsorship of the U.S. Geological Survey (USGS). An overview of the general objectives of the USGS-funded, Free-Swimming Vehicle Technology Development Program is shown in figure 2 and described in detail in reference 6. Results of studies in the indicated technological areas (figure 2) are forwarded to the concept evaluation and demonstration program, the output of which feeds into a data bank which is made available to the offshore community. The development of the testbed described in this report represents only one of the required technologies. However, the testbed will be one of the major platforms used to demonstrate and test other technological concepts.

The NOSC-designed vehicle testbed has been named EAVE WEST to distinguish it from the EAVE EAST vehicle platform being simultaneously pursued by the University of New Hampshire under the same program sponsorship (see reference 7). (EAVE is an acronym standing for Experimental Autonomous Vehicle.) The EAVE WEST design demonstrates a platform capable of taking full advantage of the higher speed capabilities of the untethered, unmanned submersible concept. EAVE EAST is designed to demonstrate the greater freedom and maneuverability possible with the untethered concept. (A diagram of the NOSC free-swimming submersible is in the appendix.)

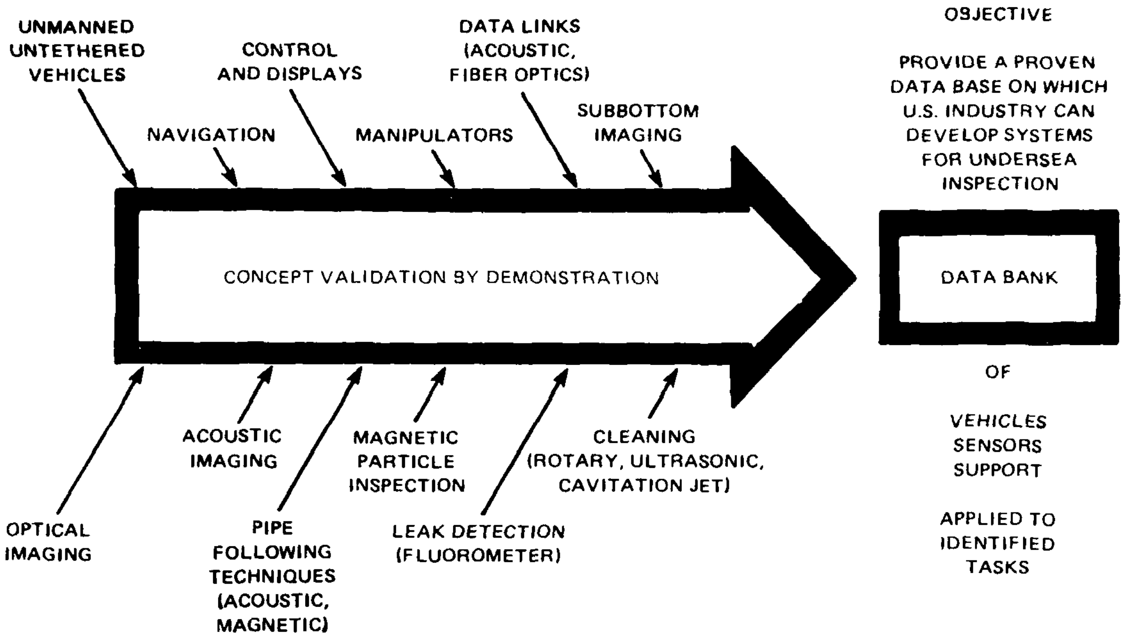


Figure 2. Technology development program, concept validation by demonstrations.

TECHNICAL APPROACH

The vehicle system that has emerged in response to the USGS goals and program philosophy is based on a general set of design concepts. These criteria were designed to produce a generalized testbed and technology demonstration platform which could be used both as a pipeline and undersea structure inspection vehicle and as a solution for potential Navy undersea search and inspection problems. Thus, technology transfer in both directions was a basic motivation for the selected approach.

DEVELOPMENT PHILOSOPHY

The basic development philosophies used in the design of the vehicle system are as follows:

Performance Criteria

1. The vehicle should be capable of operating both with and without a communication link. A testbed was required which operated under both projection and replacement system concepts.

2. The vehicle should be capable of demonstrating speeds greater than those of a tethered submersible with the same thruster power. This implies that the vehicle be basically free of cable drag and that a long and narrow configuration be adopted to reduce vehicle drag in the forward direction.

3. The vehicle should be capable of hovering and maneuvering at zero and low to medium speeds. This rules out the use of fin-controlled, torpedo-type stabilization control systems which provide only dynamic stability and do not allow the vehicle to stop and inspect an underwater object in detail.

4. The vehicle should be capable of operating relatively inexpensively for several test operations and experiments at sea. This implies that the system have an inexpensive rechargeable energy source, which is both reliable and easily maintained.

Design Flexibility

1. The vehicle should be mechanically modular to lend itself to the addition of appendages, such as television cameras, side-looking sonars, and other inspection sensors and effectors. This implies the use of a modular open-frame construction that could perhaps later be packaged in a low drag shell or fairing when the system design configuration for an optimal inspection system is finalized.

2. The vehicle design should contain a modular, easily updated, and expandable software structure that allows expansion from a single computer system to a more sophisticated supervisory-controlled configuration with some capability for autonomous operations. This implies the use of modular, block-structured, high-level languages which can be linked to form the required software program.

3. The vehicle design should allow the addition of incremental step-by-step improvements to demonstrate the progressively complex near-term advantages of improved performance over existing systems and approaches.

4. The testbed vehicle should provide a basic system design which is adaptable to a variety of uses.

Man/Machine Interface

1. Wherever possible, the vehicle system should incorporate the use of analogic controls and displays to offer the operator a more familiar adaptation to the computer. This implies the use of such approaches as joystick controls and color graphic displays.

2. The vehicle should be able to interface with the operator by using a combination of direct vehicle control and preprogrammed or autonomous control. The machine does not have to totally replace the operator at all times, but the machine should be capable of replacing the operator during routine functions or for operations such as automatic position holding.

Cost Consideration

Total system cost is of utmost importance when considering an untethered, unmanned submersible. If the basic testbed is expensive to reproduce, it will not be an economically viable alternative to existing approaches to underwater inspection. The untethered vehicle will have to be more sophisticated to allow the more complex decision-and-control capability to occur without resorting to the use of wide bandwidth communication lengths and direct operator-vehicle interaction at all times. It should, therefore, be configured so that it is reliable, maintenance free (if possible), easily amenable to changes and expansion, and adaptable to a variety of uses.

Operating costs must also be considered as part of the total system cost. One of the main advantages of the untethered approach is elimination of the costs of cable purchases, repair, handling, and replacement. A tethered vehicle also involves hidden costs, such as deck space for the cable and cable-handling system, as well as larger crew costs for handling the cable. The underlying objective of the program has, therefore, been to reduce the total system cost to achieve an economically viable approach to underwater inspection of pipelines and structures.

VEHICLE CONFIGURATIONS FOR VARIOUS MISSIONS

As a part of this development effort, several different operational scenarios, such as pipeline inspection, structure inspection, implantation of sensors with a small manipulator, and potential Navy search and recovery missions, were considered. Details of the scenarios for the intended offshore uses of the vehicle are in reference 6. It becomes immediately obvious that a single vehicle designed to accommodate all these scenarios would be large, bulky, unwieldy, and impractical. Therefore, the NOSC approach was to design a modular vehicle which was adaptable to various configurations for different

types of operations. The basic configuration required for all applications is shown in figure 3A. Figure 3B illustrates the placement of sensors and effectors for performance of a pipeline inspection mission, and figure 3C illustrates the configuration required to use a manipulator for implanting sensors on an undersea structure. Descriptions of the various sensor systems required will be given later.

SUPERVISORY CONTROL

The basic software and hardware architecture for the vehicle described in this report is that of supervisory control using a two-computer configuration. One computer is placed at the operator console and the other is placed in the vehicle, as suggested by T. Sheridan at MIT (reference 8) (see figure 4). The operator communicates with a given teleoperator system, such as a vehicle, through the intermediary of a computer. He observes displays, plans and monitors operations, and issues intermittent commands in the form of program updates through interaction with a local computer. A remote computer receives these instructions and executes them through relatively short feedback control loops. When the remote computer-driven teleoperator finishes a given set of instructions, it stops, sends back status information, and awaits further instructions. Such a configuration easily lends itself to semiautonomous vehicle operation by programming of the vehicle's computer to execute task commands through a higher and broader hierarchy. The vehicle software then breaks down these task commands to the primitive functions that it can easily execute. Eventually, the surface computer command link could be totally disconnected during an operation at sea.

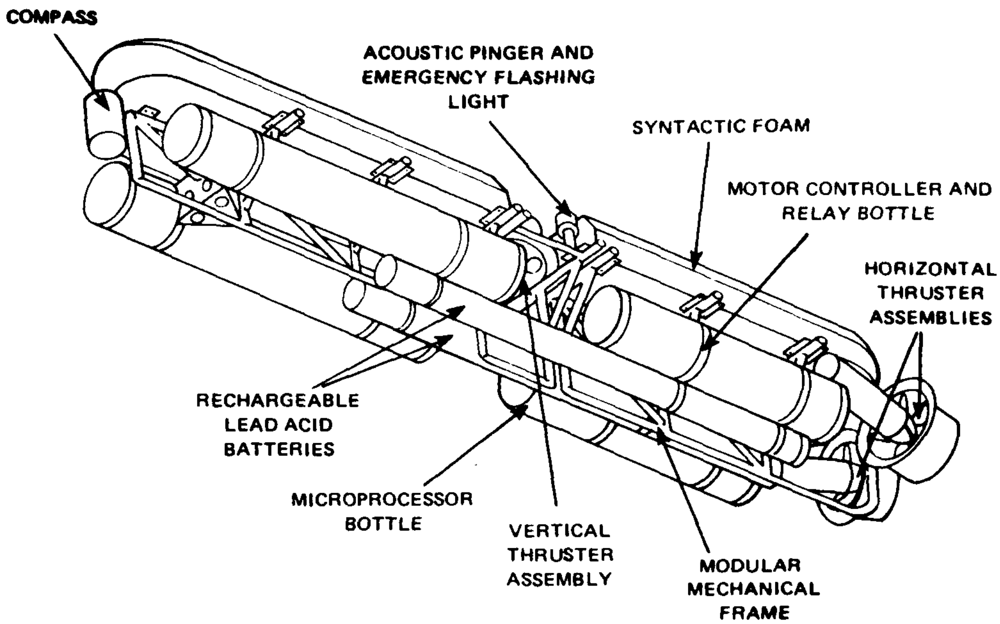


Figure 3. NOSC free-swimming vehicle concept.
Part A. Basic configuration.

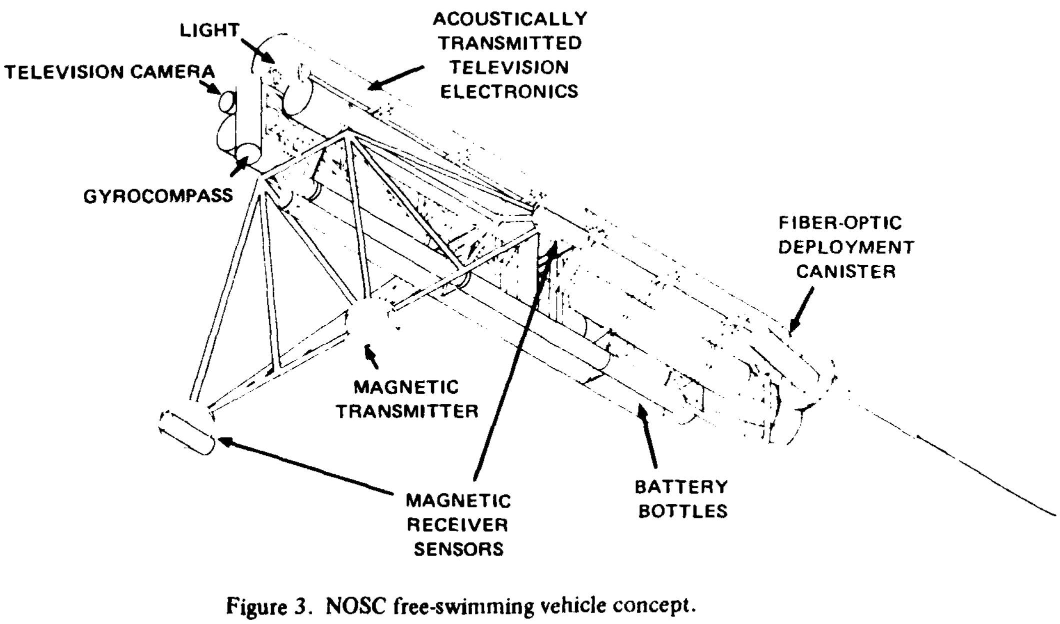


Figure 3. NOSC free-swimming vehicle concept.
Part B. Pipeline inspection system configuration.

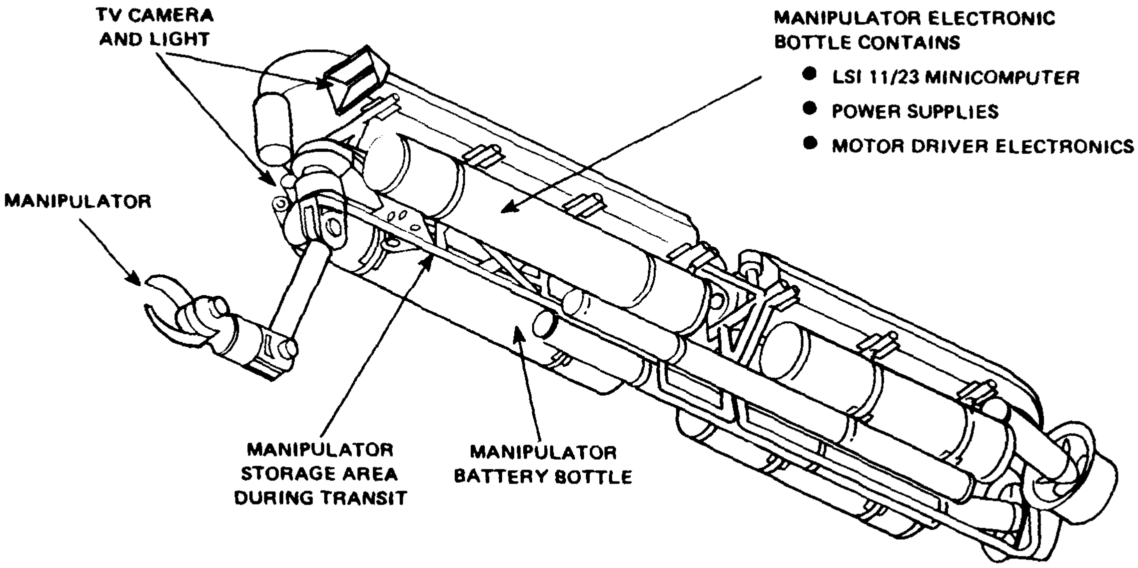


Figure 3. NOSC free-swimming vehicle concept.
Part C. Manipulator configuration.

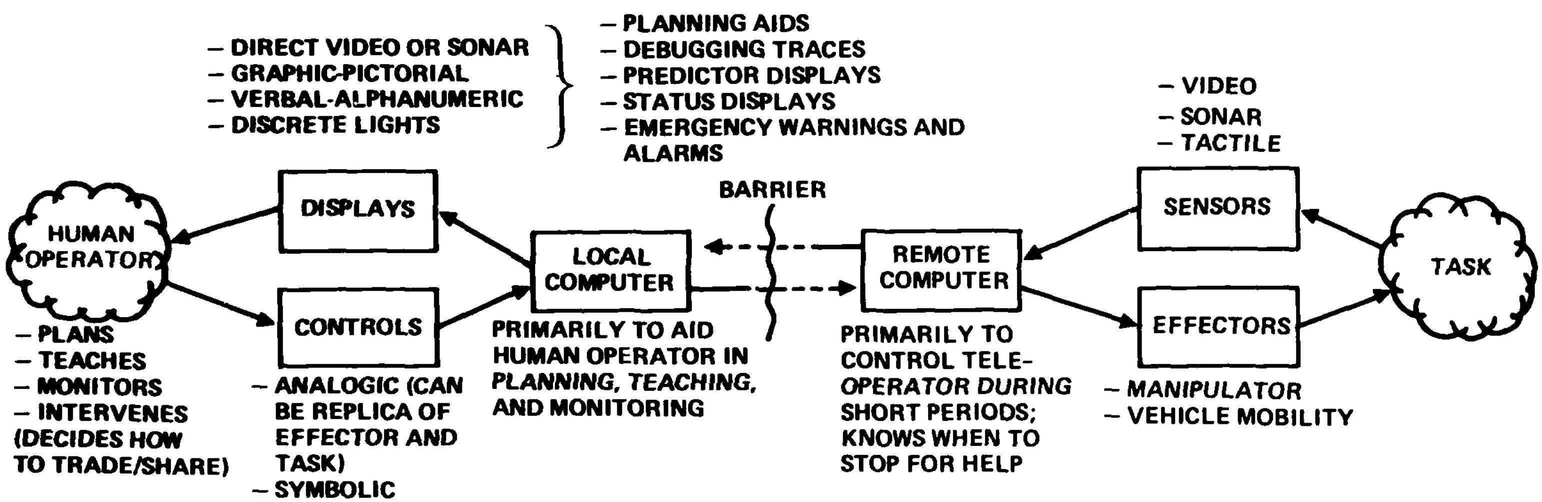


Figure 4. Supervisory control of undersea teleoperator.

SYSTEM DESCRIPTION

The general design of the EAVE WEST vehicle is based on the concepts shown in figure 3. The total system consists of a floppy disk, a computer console and keyboard, a television monitor, a junction box, a jumper cable for programming the vehicle, and the vehicle itself. The junction box contains a start switch, a reset switch, and interconnects for the vehicle cable, television output, and computer console RS232 serial link. These elements are shown schematically in figure 5, and a photograph of the total system is in figure 6.

OPERATIONAL PROCEDURE

To run the vehicle, the operator first plugs in the battery bottle and pushes the on switch located on the junction box. He then loads the console program from the minifloppy disk by using a keyboard load command. After receiving a status message indicating that the system is ready, the operator programs the vehicle by using a trajectory design program and transmits the resulting data base to the vehicle with the aid of graphic console displays and simple keyboard commands. The umbilical cable is then disconnected from the vehicle and the vehicle is placed in the water. After a preset time delay, which is chosen by the operator during the trajectory design phase, the vehicle begins its preprogrammed run. The operator can then interact with the vehicle through a communication link in any of three ways:

1. He can design a trajectory in the console memory, transmit the new program trajectory data base to the vehicle, and initiate a new preprogrammed run.

2. He can modify the present program trajectory in the console memory, transmit it to the vehicle, and reinitiate a modified preprogrammed run.

3. He can take over real-time control by using the joysticks mounted at the console keyboard while monitoring progress with the symbolic and analogic console displays and the television monitor.

Thus, the operator can choose at any given moment to run the vehicle in either the projection or autonomous mode.

DESIGN STRUCTURE

The mechanical, electrical, and software structures of this submersible, designed for flexibility and adaptability, are summarized in table 2.

Mechanical Configuration

The vehicle, shown in figure 7 resting on its wooden laboratory support frame, is a 9-ft long, T-shaped, open-frame configuration mounted to a series of syntactic foam blocks for buoyancy. The T-shaped frame was used to minimize the total weight of the frame and was made in three sections to allow

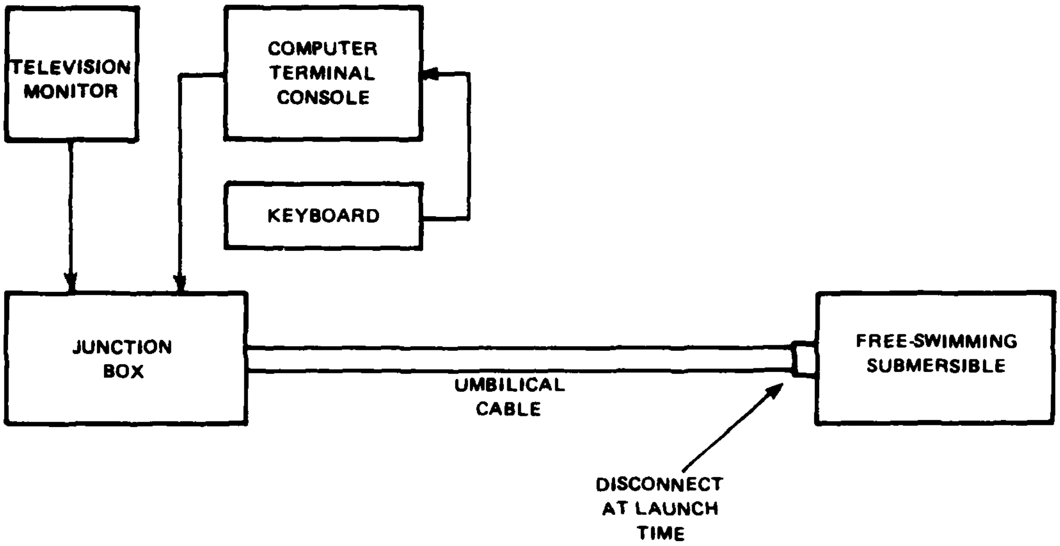


Figure 5. Basic elements of the NOSC/USGS free-swimming submersible system.

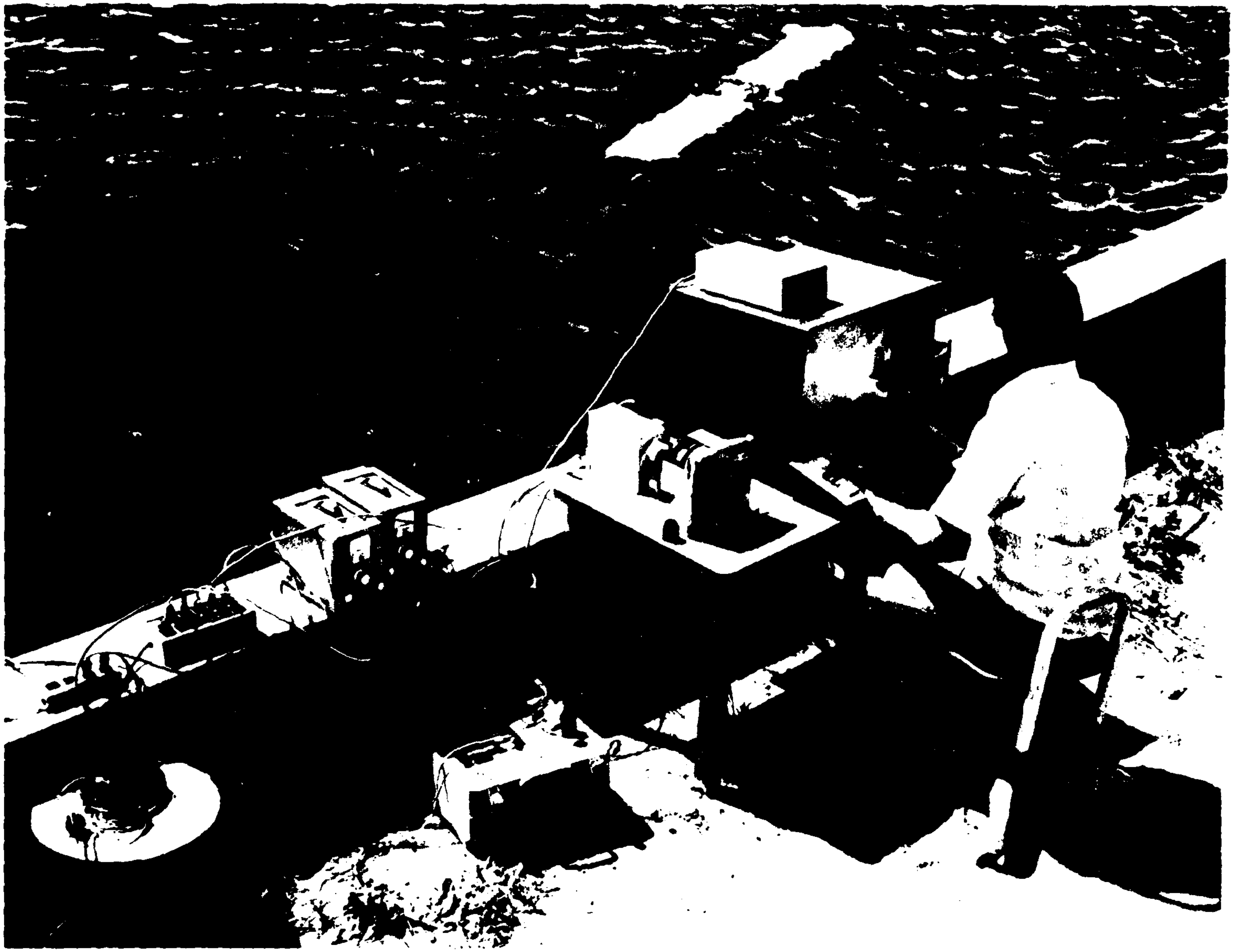


Figure 6. NOSC/USGS free-swimming submersible system.

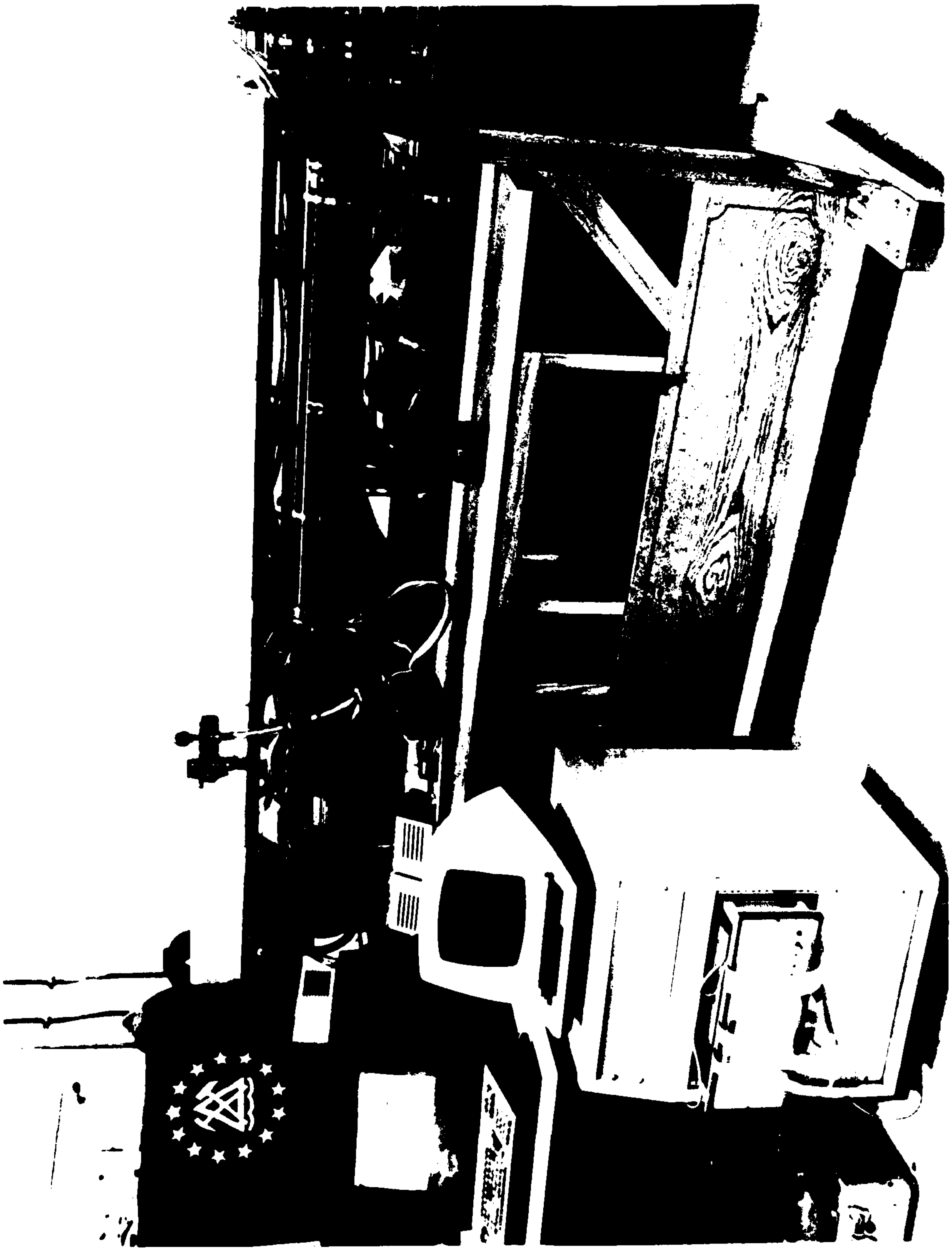


Figure 7. NOSC free-swimming vehicle's platform

Design Structure	Characteristic
Mechanical	
Size	22 in high, 22 in wide, 9 ft long, easily adapted to a fairing
Weight	450 lb
Buoyancy/foot extension	25-lb/ft extension in length
Total buoyancy of foam	180 lb positive
Frame construction	T-shaped, sealed, welded, neutrally buoyant (can withstand depths to 2200 ft)
Electronic canisters	7-in-outside-diameter pressure housings designed for 2200-ft operations 2 30-in-long bottles (mounted aft) 2 30-in-long bottles (mounted forward)
Electrical	
Energy storage	Gates lead-acid batteries (series of 2-V, 25-A-hr batteries)
Control system	8080 microprocessor system
Control sensors	Magnetic-pipe follower, depth, heading, leak detectors
Present data sensors	Television, still photo, super 8 movie camera
Potential data sensors	Space has been allocated for Klein side-looking sonar
Software	
Language	8080 Assembly Language, PL/M, and FORTRAN
Structure	Flexible, modular, construction linked together to provide supervisory control of submersible

Table 2. NOSC/USGS Free-Swimming Submersible: Mechanical, Electrical, and Software Characteristics Summary.

Design Structure	Characteristic
Memory length required	
Vehicle	6k of program firmware located in PROM 2k of scratch-pad RAM.
Console	24K of program operated in RAM interactive with minifloppy disk.

Table 2. NOSC/USGS Free-Swimming Submersible: Mechanical, Electrical, and Software Characteristics Summary. (Continued.)

lengthening of the vehicle to accommodate 25 lb of additional payload per foot of extension. The frame itself, weighing only 10 lb in water, is constructed of sealed, welded aluminum tubing. The open-frame configuration has the advantage of allowing the addition of new sensors or payloads by simply strapping them onto the frame with little modification. A long, narrow configuration was chosen to allow for minimum drag in the water. It is adaptable to a closed external skin which would reduce the drag if even higher speeds were required in the future. Four 7-in-diameter, underwater, 1-atmospheric pressure housings, containing most of the vehicle electronics, are strapped to support brackets welded onto the main frame. Two 3-in-diameter bottles containing the battery power pack are attached to brackets bolted to the lower portion of the frame; this provides a reasonably good separation between the center of gravity and the center of buoyancy. These battery housings are approximately 7 ft long and span almost the entire length of the vehicle frame. They are 1-atmospheric pressure housings which are purged with nitrogen prior to launch to remove any possible danger of a hydrogen-oxygen explosion.

There are three thrusters which provide 3 degrees of freedom in the water (two horizontal thrusters and one vertical thruster). The horizontal thrusters are canted 15 degrees to provide a smaller turn radius. The motor housings are oil-filled, pressure-compensated units designed and fabricated at NOSC with commercially available Kort nozzles and propellers on each DC motor. The canisters and motors are electrically interconnected using oil-filled, pressure-compensated cables and connectors.

A combination of 32- and 24-lb/ft^3 syntactic foam is used to provide about 180 lb of buoyancy for the vehicle. The frame is bolted directly to this foam with aluminum inserts. Metal parts exposed to the water are hard-black anodized aluminum. The entire configuration is adjusted by trim weights to be approximately 8 lb postively buoyant. The vehicle, designed to operate down to a depth of 2200 ft, submerges and maintains depth using the 20 lb of thrust from the vertical motor. In an actual operation at such depths, it is not anticipated that the vehicle would be driven down the entire distance by the vertical motor. Instead, a weight would be used to aid the vehicle in

reaching the approximate depth. It would then be released, allowing the vertical thruster to maintain depth until the end of the mission. The normal positive buoyancy of the vehicle, aided perhaps by dropping additional weights, would then allow it to return to the surface. Such methods would prolong the mission duration at depth by conserving battery power while descending and ascending.

Electrical Configuration

An electronic block diagram showing the hardware implementation of the supervisory-control concept is in figure 8. An attempt was made to use commercially available computer electronics wherever possible to reduce manufacturing costs, increase reliability and maintainability, and allow for easy adaptation of the design concepts and software.

The basis of the topside electronics is an Intecolor 8051 color graphics display terminal and its associated minifloppy disk drive and keyboard. This terminal costs only $4995, yet it has a tremendous amount of available software and input/output flexibility, plus 24k of random access memory for user programs. It is essentially a very inexpensive microprocessor system with keyboard and display that can even be used as a development system. The color graphics capability is not necessary for the basic requirement for a topside computer console that conserves program space in the vehicle and implements a supervisory-controlled design. However, the graphics capability has provided a better man/machine interface by making it possible for the operator to visualize items such as the pattern programmed into the vehicle, the movement of the vehicle with respect to the preprogrammed path, analogic displays, and color accentuation of pertinent parameters.

Four bottles mounted on the frame directly beneath the floatation material contain the electronics which drive the various sensors and effectors. The two shorter bottles (30 in long) at the stern house the basic electronics required for all configurations of the vehicle. The rear starboard bottle contains microprocessor control electronics, while the port bottle contains the motor controller electronics and switching relays. The longer bottles (42 in long) in the front of the vehicle house the sensor and communication system electronics. The contents of these bottles change for the various vehicle configurations shown in figure 3.

The basis of the vehicle control electronics is the microprocessor electronics card rack shown in figure 9, which contains the commercially available printed circuit cards plus one NOSC-designed interface card (table 3).

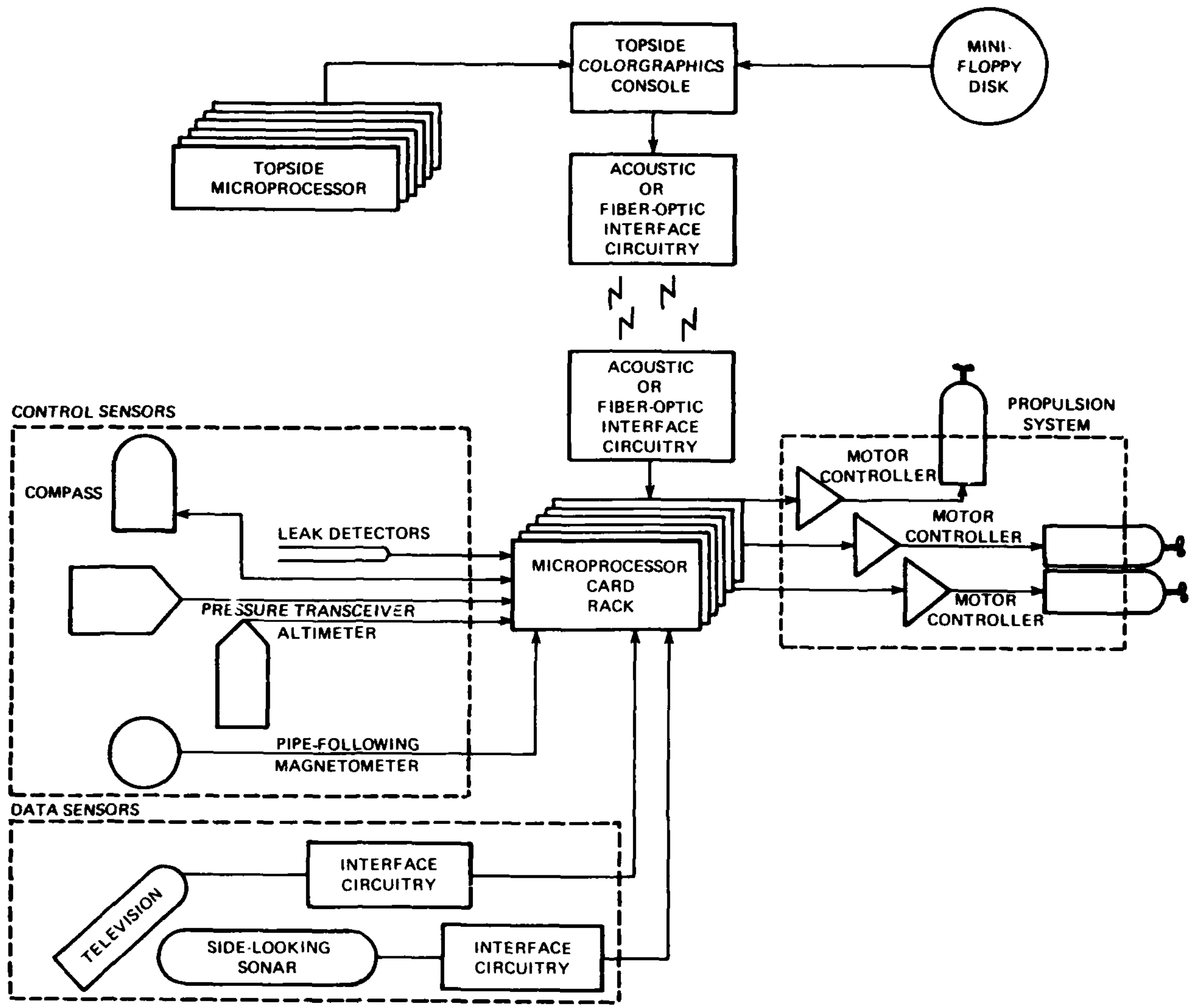


Figure 8. Supervisor-controlled free-swimming submersible concept.

Figure 9. Microprocessor electronics card rack

Number Used	Type	Manufacturer/Part Number
1	Microprocessor card (4 kilobytes of PROM)	Prolog 8821
1	TTL input buffer card (4 inputs)	Prolog 8114
1	TTL output latch card (4 outputs)	Prolog 8115
1	8-bit A/D converter card (16 inputs)	Burr Brown MP4216
1	12-bit A/D converter card (16 inputs)	Analog Devices RTI-1220
2	8-bit D/A converter card (2 outputs)	Burr Brown MP4102
2	Relay output card (8 switches)	Prolog 8402
1	16k ROM/RAM card (using Texas Instruments 2716 PROMs)	Prolog 8820
1	4k CMOS RAM card	Prolog 8122
1	Serial communications (UART) card	GIULI COM 412
1	Interface control card	NOSC

Table 3. Printed Circuit Cards for the Vehicle Microprocessor System.

The microprocessor is used to compare programmed run time, heading, depth, and run sequence input data with measured data originating from an on-board clock, fluxgate updated gyro compass, depth sensor, and run sequence pointer, respectively. The microprocessor generates digital 8-bit error signals between the programmed values and the measured values, and issues 8-bit error signals to the appropriate linear motor controllers according to a linear control algorithm. The motor controllers then power the pressure compensated, 1/4-horsepower, 24-V DC motors which directly drive the propellers.

Primary power is supplied to the vehicle by a series of 2-V, 25-A-hr, Gates rechargeable lead-acid batteries located in the two long containers mounted beneath the vehicle. These provide 26 and 14 V DC which drive the +5-V and +15-V inverter power supplies and the appropriate regulators to run the other electronics. The present battery pack weighs about 77 lb. Although this pack could be replaced with lithium cells having the same approximate volume but with about five times the energy, they would be nonrechargeable primary cells and would be relatively expensive to replace.

Software Structure

The basis of the NOSC free-swimmer control system is the software program presently stored as firmware in 6 kilobytes of programmable read-only memory (PROM), 2 kilobytes of random access memory (RAM) in the vehicle microprocessor, and 24 kilobytes of RAM in the console microprocessor memory. A brief summary of the software characteristics has been included in table 2. Originally, the software was programmed in 8080 assembly language. When PL/M was made available by INTEL, Inc., it was adapted as the primary programming language for the submersible. PL/M is a microprocessor compatible subset of the PL-1 high-level programming language. It is a modular-structured, high-level compiler which allows a high degree of flexibility for modifying and adding to the scope of the free-swimmer software with a minimum of software development cost. Figure 10 depicts the system's distributed or two-processor

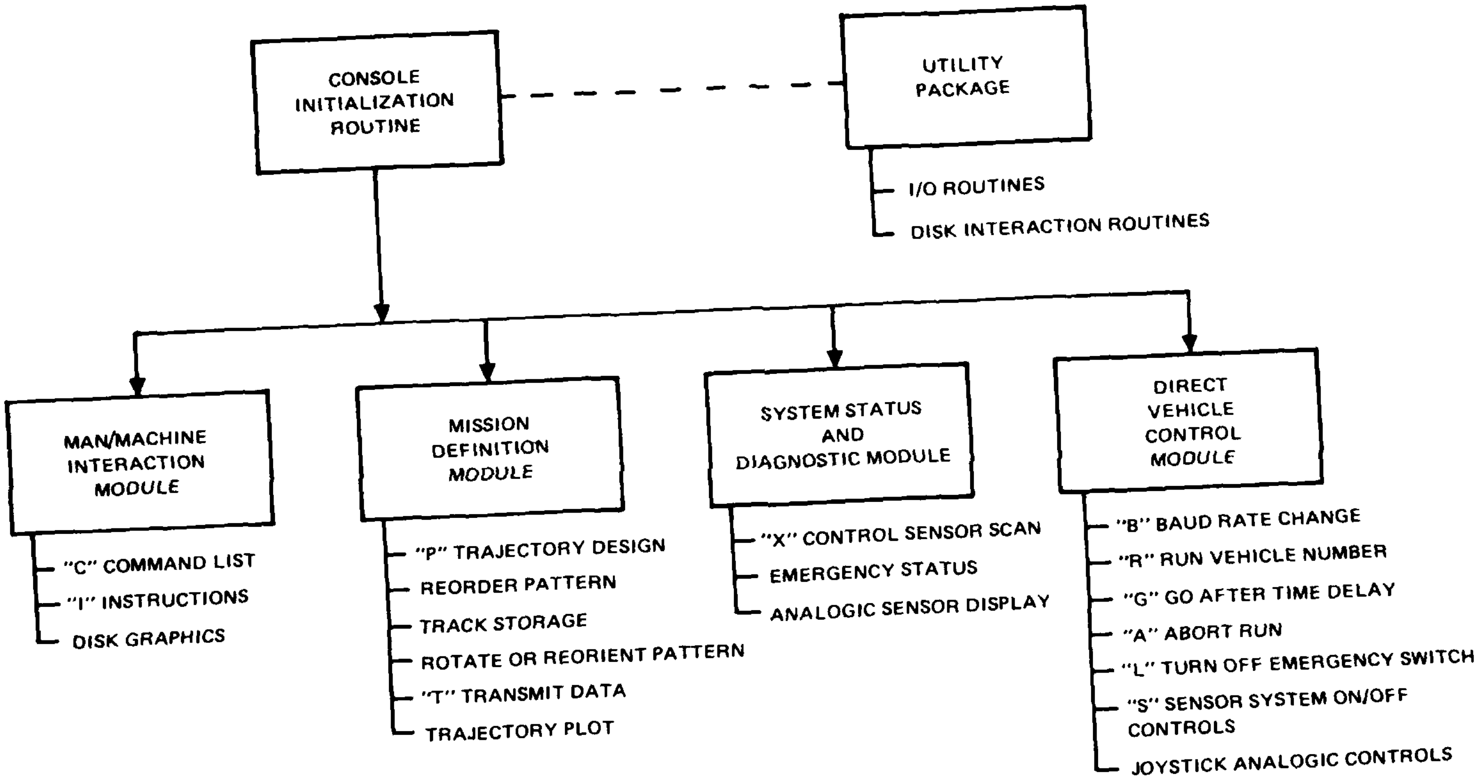


Figure 10. Free-swimmer two-processor software architecture.
Part A. Console programs.

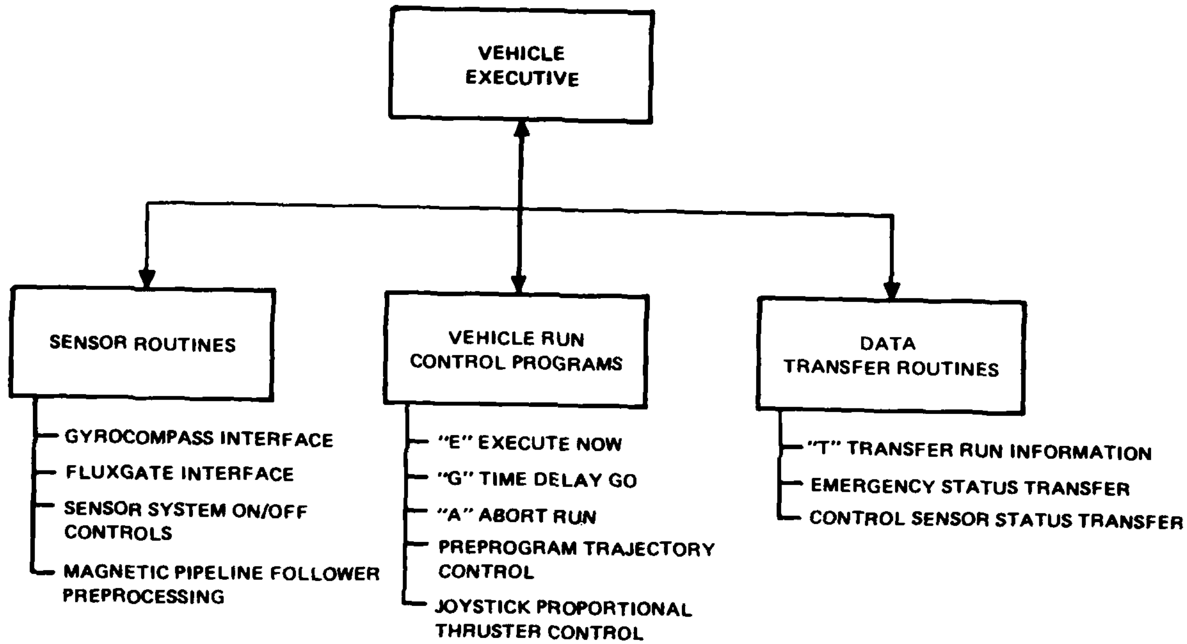


Figure 10. Free-swimmer two-processor software architecture.
Part B. Vehicle programs.

configuration. The console routines consist of a separate series of linked programs from the vehicle's routines. Each separate software package is designed to communicate with the other without the use of interrupts.

CONSOLE OPERATOR INTERACTION ROUTINES. The console software program (figure 10A) consists of four major categories of routines: mission definition module, a direct vehicle control module, a system status module, and diagnostic module. In addition, man/machine interface routines have been programmed to demonstrate the versatility and analogic presentation capabilities of the color graphics console approach.

The mission definition module consists of a trajectory design program, a library of preprogrammable patterns, and a method to transmit the data for running this trajectory to the vehicle. The purpose of the trajectory design program is to create and manipulate the data base representing the desired preprogrammed trajectory of the vehicle. Only the essential parameters of this data base are then transmitted to the vehicle by the console computer. The trajectory design program allows the operator to choose a series of preprogrammed tracks or to generate new patterns for the vehicle to execute. This operator interactive program is presented on the screen in the format shown in figure 11. The existing patterns now programmed in memory are Taxi Straight, Figure 8, Parallel Path, Square, and Hexagon.

Each pattern consists of a series of legs which represent straight-line runs at a given heading and a given depth for a specified period of time. The vehicle presently travels at no more than 2 knots and this time is usually a matter of only a few seconds. Each leg also indicates which switches are to be turned on or off during the run. At the end of each leg, the vehicle will progress to the next leg until the total pattern has been completed. The vehicle will then proceed to execute the next pattern until the entire trajectory has been completed. A series of 30 different patterns is possible. To help the operator in visualizing the trajectory chosen, a means of plotting this trajectory has been incorporated into the trajectory design program. Each individual pattern can be modified, rotated, deleted, and reordered in sequence, and the total trajectory can be graphically displayed at any point in this process by using simple keyboard instructions and answering computer prompting questions as required.

Once the vehicle itself receives the preprogrammed data base, it can be directly commanded by the operator to start its run (with or without a predetermined time delay), abort a run, or execute direct vehicle control by the operator who uses the joysticks mounted at the sides of the keyboard. These are the types of control commands possible using the direct vehicle control module shown in the software structure diagram in figure 10B. In addition, there is direct control of the data sensor switches available from the keyboard. Although direct vehicle control still uses the supervisory-control architecture to perform the various functions from the console, use of these controls changes the vehicle to the projection mode as defined earlier.

The status and diagnostic routine modules provide the operator with a summary of the status of the control sensors, vehicle electronic voltages, and emergency sensors. The format is as shown in figure 12. In figure 12, analogic displays are used to provide the operator with the feeling that he is

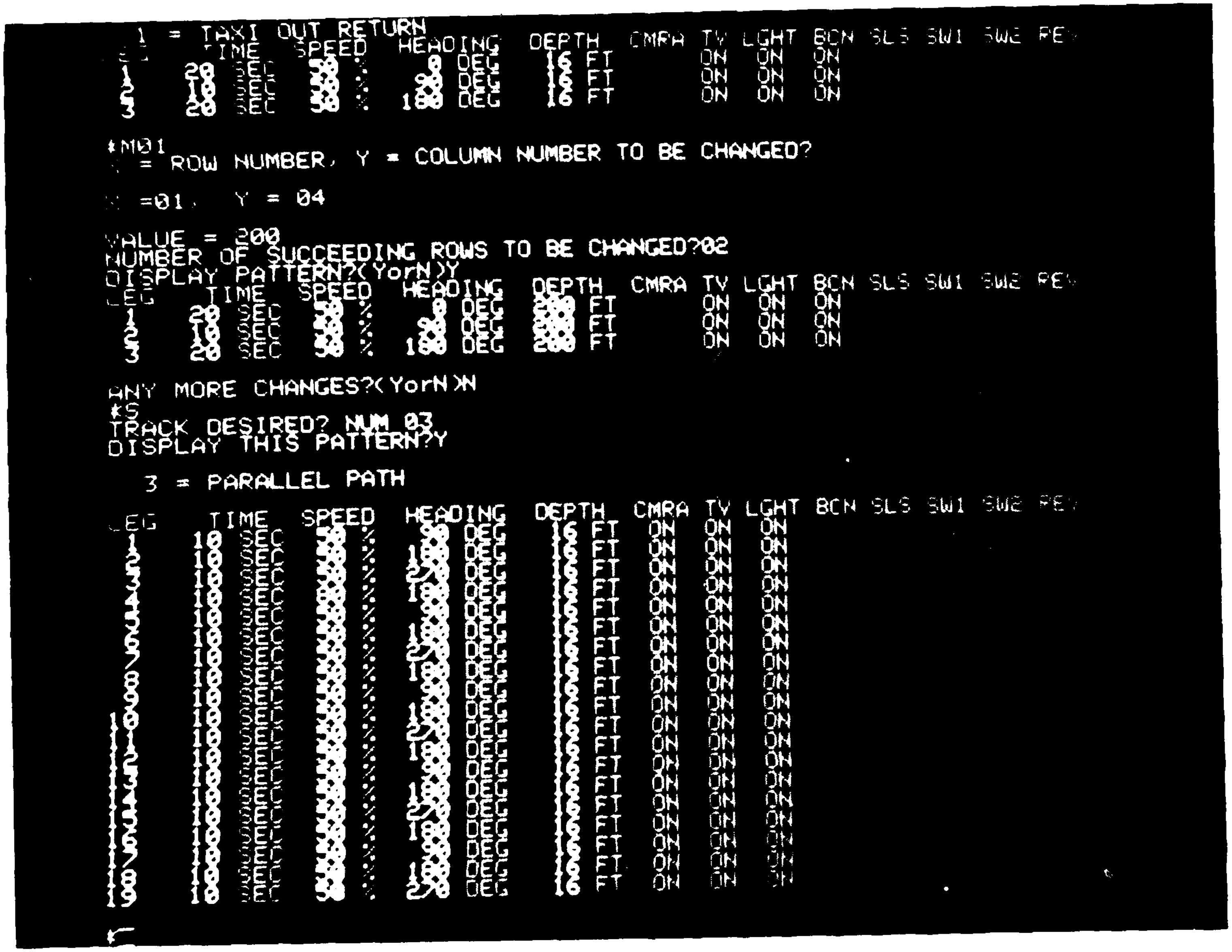


Figure 11. Example of operator/console interaction display on CRT screen during track development

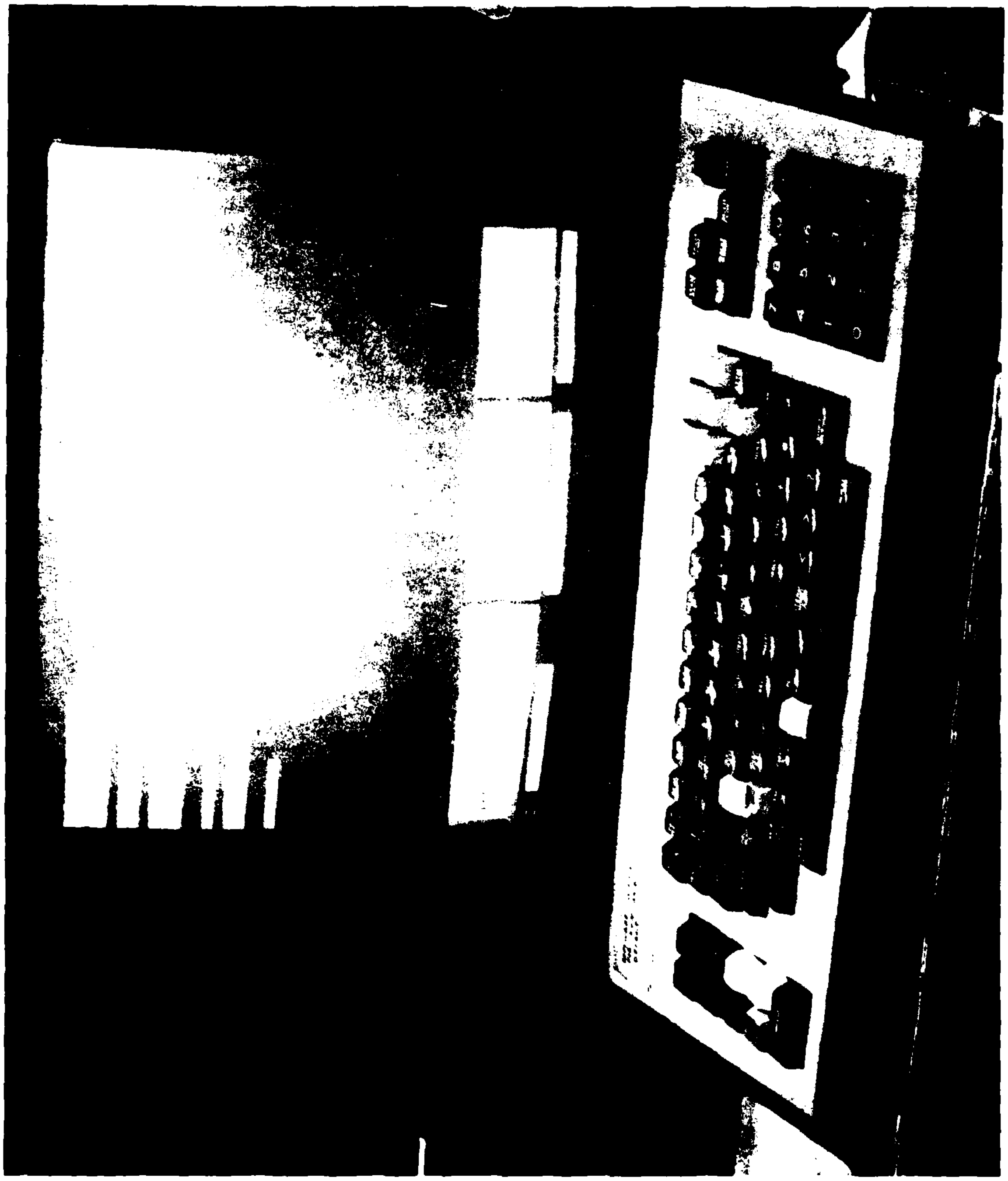


Figure 12. Analogic display of status and diagnostic routine module.

dealing with such familiar displays as compass heading, a heading error indicator, and an analog speed indicator. Actually, the same data have been provided within the symbolic digital notation at the top of the display screen, but they are much harder for the operator to decipher. The entire display is available to the operator by depression of the "X" key on the console. Graphic display of the meters is performed through interaction with the minifloppy disk.

VEHICLE ROUTINES. The software structure of the vehicle routines which actually operate the vehicle after the umbilical cable is disconnected and the run has begun is shown in figure 13. The microprocessor first compares the programmed values of the heading and depth with the actual sensor readings, sending the appropriate error signals to the thrusters through the appropriate digital-to-analog converter. It then checks a series of emergency conditions such as leaks, overpressure, or low battery voltage. If the emergency status is bad, the processor aborts the mission, turns on an emergency beacon, and comes to the surface. If the status is good, it checks for a possible abort word from the console which might arrive through an acoustics or fiber-optic communication link (to be installed in the future). If all is satisfactory, the vehicle will check a clock chip to determine if it is time to start a new leg. If not, the program will continue to cycle through as before; otherwise, it will input the next leg of data and begin its execution.

At present, vehicle navigation is done primarily by dead reckoning. However, it would be easy to install a "strap down" inertial navigation system using this same software structure, as time and funding permit. Items such as an error-generating program for altitude, a current sensor, and doppler navigation would be straightforward additions to the present software structure.

PERFORMANCE CHARACTERISTICS

A summary of the performance characteristics for the NOSC free-swimming vehicle is in table 4.

The mechanical configuration is such that the vehicle can be packaged within a cylindrical fairing in the future to increase its in-water speed from its present 1.8 knots to a projected 5 knots. These figures represent the speed at any depth down to the maximum operating depth of 2200 ft, since there is no cable drag to slow the vehicle as with tethered submersibles.

Likewise, the current 1-hr run duration can be extended to 4.4 hr by simply replacing the present inexpensive, rechargeable, lead-acid battery pack with a lithium battery pack currently under development. The approximate payload capacity of the vehicle is currently 25 lb. This is also flexible in that approximately 25 lb of additional payload can be added for every foot the vehicle is increased in length.

The configuration of three thrusters allows 3 degrees of freedom in the water. The thrusters are canted 15 deg to allow a shorter turning radius. Turning radii of less than the length of the vehicle (9 ft) were observed during actual tests.

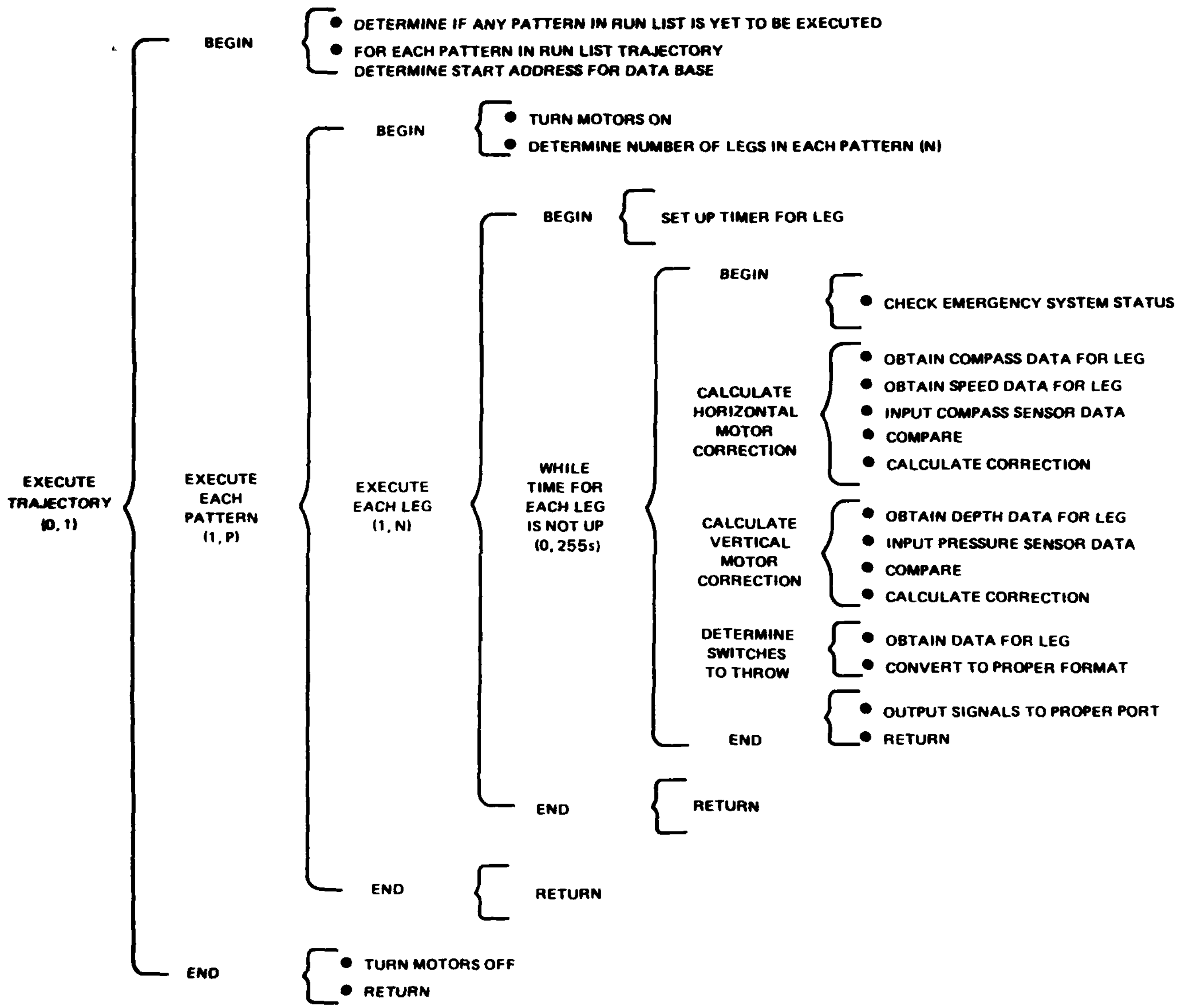


Figure 13. Warnier-Orr diagram for vehicle's preprogrammed trajectory execution routines.

Parameter	Characteristics
Speed	Maximum: 1.8 knots without fairing 5 knots with fairing Minimum: 0 knot
Duration	1.3 hr using present lead-acid batteries 4.4 hr using lithium battery now under construction
Turn radius	10 ft (approximate)
Load capacity	25 lb/ft of extension
Launching platform	Existing platforms
Maximum depth	2200 ft
Autonomous functions	Preprogrammed trajectory execution Pipeline-following capability Automatic response to emergency sensors

Table 4. Summary of NOSC/USGS Free-Swimming Vehicle's Performance Characteristics.

SUBSYSTEM BREAKDOWN

A brief functional breakdown describing some details of existing and planned capabilities will now be given. All subsystems are part of the technologies being investigated for potential use with unmanned, untethered submersibles (figure 2). Other aspects of these technologies, such as acoustic communication and bottom transponder navigation, are being investigated by the University of New Hampshire and will be tested or demonstrated on their EAVE EAST submersible (see reference 7).

Communication Subsystem

For entirely autonomous operation before launch, the communication link to the EAVE WEST vehicle is simply an umbilical cable which is disconnected after preprogramming the submersible and transferring the resulting data base to the vehicle. The umbilical cable is disconnected while the vehicle is executing a preprogrammed time delay.

The use of fiber optics as a communication link to this submersible is being investigated. This link is an attempt to fulfill the real-time console communication requirements through an extremely small, lightweight, low-drag, single fiber-optic strand. This fishing-line-size cable will be able to handle all data and control requirements of the entire vehicle at the full bandwidth of existing visual data sensors. If this is achieved, it will be

possible to take advantage of a real-time high bandwidth data link; use existing, relatively inexpensive data sensors, such as television cameras and sonar systems; and not suffer the disadvantages of high cable drag experienced in tethered submersibles. For the application of a pipeline survey and inspection vehicle, where the submersible will be deployed from a compact canister along relatively straight-line runs for long distances, this approach is quite feasible and attractive. Up to 5 km of cable can be stored on a coil which is approximately 3 in long with an outside diameter of 8 in and an inside diameter of 5 in. For the application of structures inspection, this approach is promising but not without fault. Cable entanglement within the structure can break a fiber-optic link with a 6-lb tensile strength; however, with some autonomous capability the free-swimming submersible could conceivably navigate out of the structure. Use of a fiberglass-sheathed, fiber-optic cable with a 100-lb tensile strength is also being investigated for potentially reducing the risk of breakage due to entanglement.

Components of the fiber-optic link are shown in figure 14. Subtechnologies to this investigation are listed below:

1. A method involving a high signal-to-noise ratio (SNR) for modulating large bandwidth signals for transmission of the uplink. NOSC's approach has been to use pulse frequency modulation (PFM) (see reference 9).

2. A duplex operation for sending relatively low bandwidth command signals to the vehicle and for receiving relatively high bandwidth visual sensor information at the operator console.

3. Penetration of the fiber-optic link into the underwater containers; the penetration method must be easily disconnected and operate at a depth of 2200 ft or greater.

4. Deployment of the fiber-optic cable from the submersible without exceeding the maximum tension of the cable and without causing vehicle drag.

5. Precision winding of the cable in the laboratory for installation in the deployment canister. The resulting coil must incorporate pretwisted winding to allow deployment without creating kinks.

6. A way to avoid cable entanglement in the vehicle propellers.

The results of the investigation of item 1 are discussed in reference 1. The investigation of the remaining items and inspection of pipelines and structures are discussed in reference 10.

Approximately 80 percent of the work required for complete demonstration of a deployed, fiber-optic link on the EAVE WEST vehicle has been completed. This includes the PFM techniques, duplex operation, penetration to the vehicle housing, and a precision fiber-optic winding machine. Preliminary tests of possible deployment methods have been made, and the vehicle has been operated

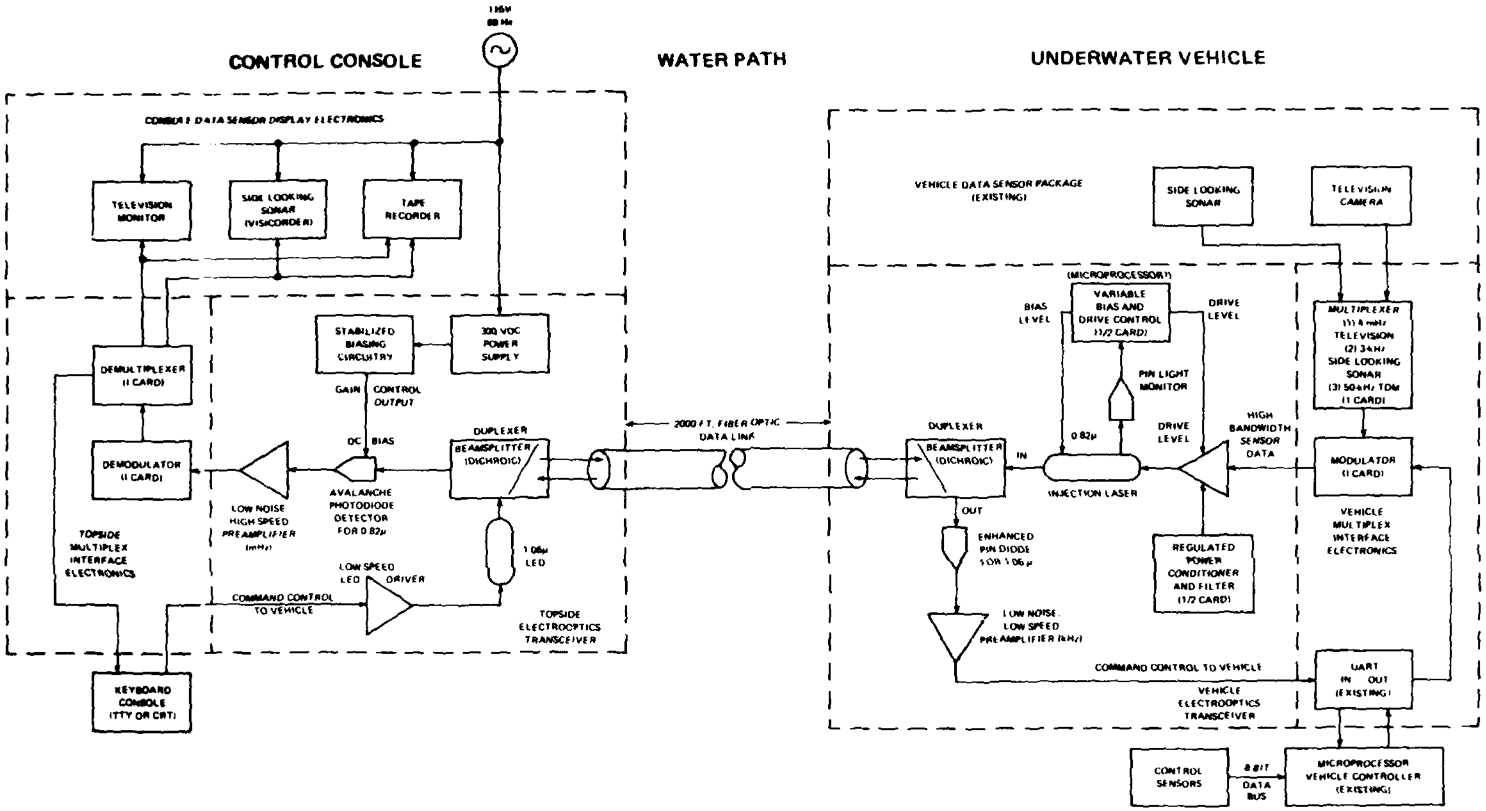


Figure 14. Duplex fiber-optic link for free-swimming vehicle.

in water in a real-time control mode with a good video picture from an underwater television camera mounted to the vehicle with a small, twisted-pair tether. Thus, since the fiber-optic subsystems have been fabricated and individually tested, all that remains is to install and test the various components on the submersible.

Navigation Subsystem

Three basic navigation methods have been designed for the EAVE WEST submersible: preprogrammed trajectory and magnetic pipe following when operating under the autonomous mode and visual orientation when operating under the projection mode.

The vehicle's preprogrammed trajectories are presently executed through a dead-reckoning navigation sensor, i.e., a magnetic compass, a depth sensor, and an internal timer are used to navigate from one point to another. Such an approach, of course, leads to drift errors because of ocean currents. If, however, an off-the-shelf bottom transponder navigation system were added to the vehicle, software programming of the control equations could be accomplished in the same general manner used for the existing dead-reckoning approach. Error signals would be generated to compensate for the difference between a desired position and the actual position measured by the navigation system. The cost of such a system could, however, approach the present development cost of the vehicle. Because of this and also to avoid redeveloping technologies already existing, a simple dead-reckoning approach was installed for demonstration purposes.

A magnetic-pipe-following system will soon be incorporated in the vehicle to allow autonomous tracking of a pipeline located either on the ocean bottom or buried beneath it. The system uses magnetic induction to autonomously follow a 48-in pipeline at a vertical distance of up to 18 ft. The magnetic sensor and transmitter are separated from each other and the vehicle to limit interference (see figure 3). A block diagram of this approach is shown in figure 15. The system uses two receivers and one transmitter operating at frequencies selectable from 40 Hz to 4 kHz. The basic problem involved is to discriminate the received signals from the transmitting signal with as high a signal-to-noise ratio as is possible. Details of this sensor system will be discussed in a separate report.

A television camera has been installed on the vehicle to provide a visual means of navigation along a pipeline or within a structure when the vehicle is operated in projection mode. Transmission of the signal to the console operator will be via the fiber-optic link when it is installed and operational. In addition, however, NOSC is pursuing a means of transmitting the video acoustically to the surface. Display of 128-by-128 and 256-by-256 picture elements has been tested and determined to operate to depths of 4000 ft (reference 11). This is another technology subelement being investigated as a part of the free-swimmer technology development program.

Data Acquisition Subsystem

A Subsea Systems, Inc., silicone diode array camera with a 600-line resolution capability and a 75-W quartz iodide light is presently installed as one of the major sensors for visual inspection of pipelines and structures. A

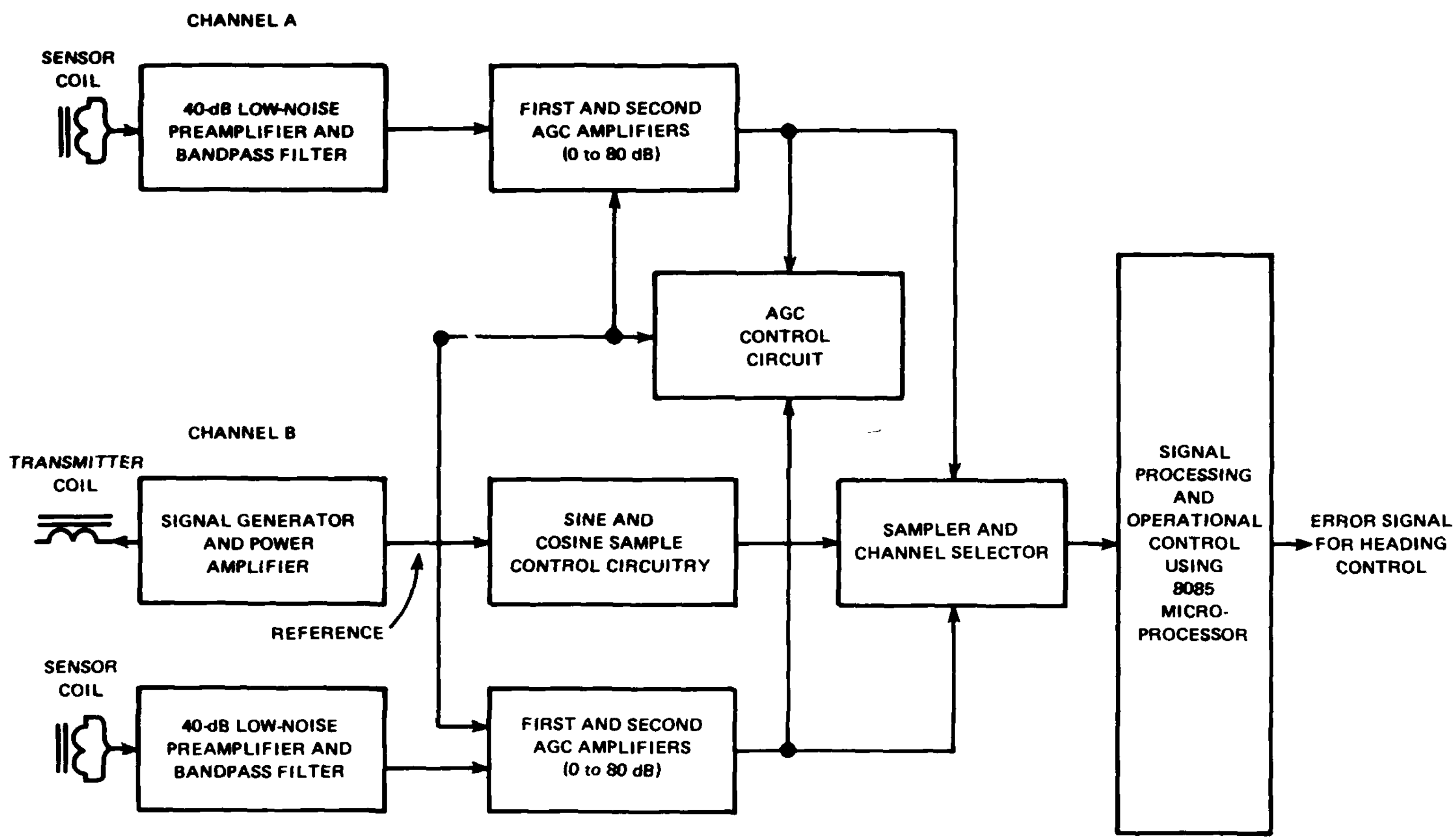


Figure 15. Automatic pipeline-following system.

Remote Ocean Systems Super-8 film camera is used for gathering both still and motion picture photographs on keyboard or preprogrammed command. The future importance of the data acquisition subsystem is not what or how many sensors are incorporated, but whether these can be used to provide better autonomous control of the submersible and whether information concerning structural faults or leaks can be automatically derived to alert an operator as to their location. Such technologies will be investigated in the future as a part of this program.

Physical Tasks Subsystem

With the intent of using EAVE WEST as a testbed and with financial support from both the Office of Naval Research and NOSC's Independent Exploratory Development funding, a manipulator is being developed. The electrically driven manipulator (figure 16) has 5 deg of freedom in addition to jaw closure. Degrees of freedom from top to bottom include shoulder pivot and rotate, elbow joint, wrist rotate, and wrist pivot. Its six pressure-compensated, oil-filled motors incorporate position feedback potentiometers and harmonic drive gearing. Total lift capability is 25 lb vertically and approximately 8 lb at full extension. The total weight of the manipulator is 34 lb in air. Motor housings are fabricated of hard black-anodized aluminum, whereas the other support components are composed of fiberglass with the arm itself filled with syntactic foam to conserve weight in water, which is about 30 lb. The arm itself has already been fabricated and tested.

Plans are to drive the arm in a supervisory-controlled fashion using LSI 11/23, 16-bit minicomputers packaged both in a vehicle housing and at the surface console area. This will reduce the vast amount of bandwidth and operator training otherwise required when using a manipulator on a remotely controlled vehicle. Computer software is being supplied by MIT as an adaptation of MIT's effort in supervisory-controlled manipulators and man/machine interface for ONR (reference 12). A diagram showing the supervisory-controlled manipulator as designed for integration with the LSI 11/23 printed circuit cards and control components is in figure 17. The device will be installed on the vehicle, as indicated in figure 3C. Although the manipulator is shown mounted at the front of the vehicle to allow reaching into crowded areas, system modularity will also allow it to be mounted at the center of the vehicle. This would especially be useful for picking up instrument packages or seafloor samples when operating along a pipeline or in an open area.

Technological problems to be solved include the following:

1. The use of a measurement arm to facilitate operation when relative motion is present between the vehicle and the work site.

2. The use of electrically induced compliance to facilitate final approach and grasp operations.

3. The use of low bandwidth measurements of the position of the manipulator's endpoint to update slow scan television pictures as to the continual status of the manipulator position.

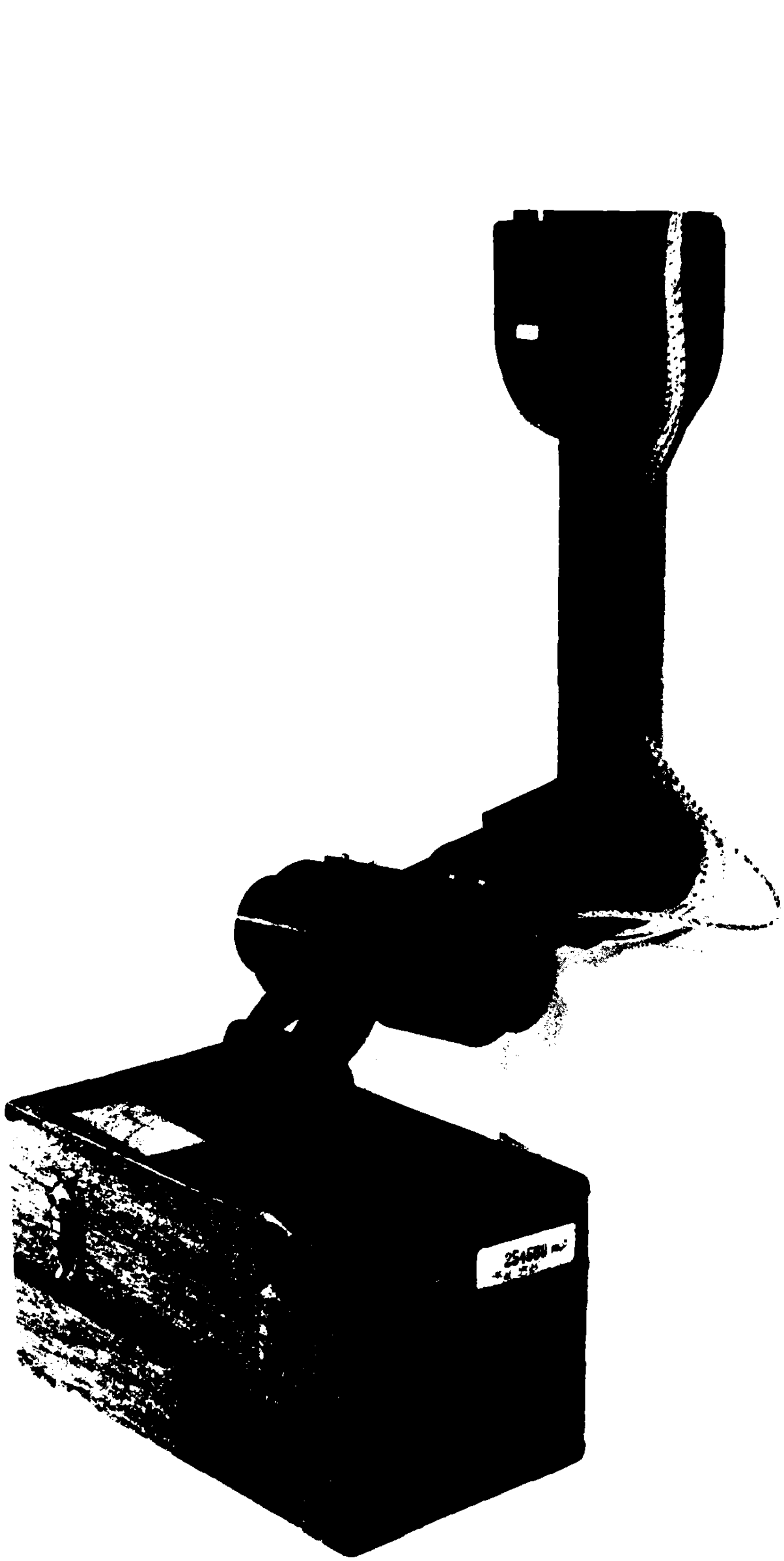


Figure 16. Electrically driven manipulator.

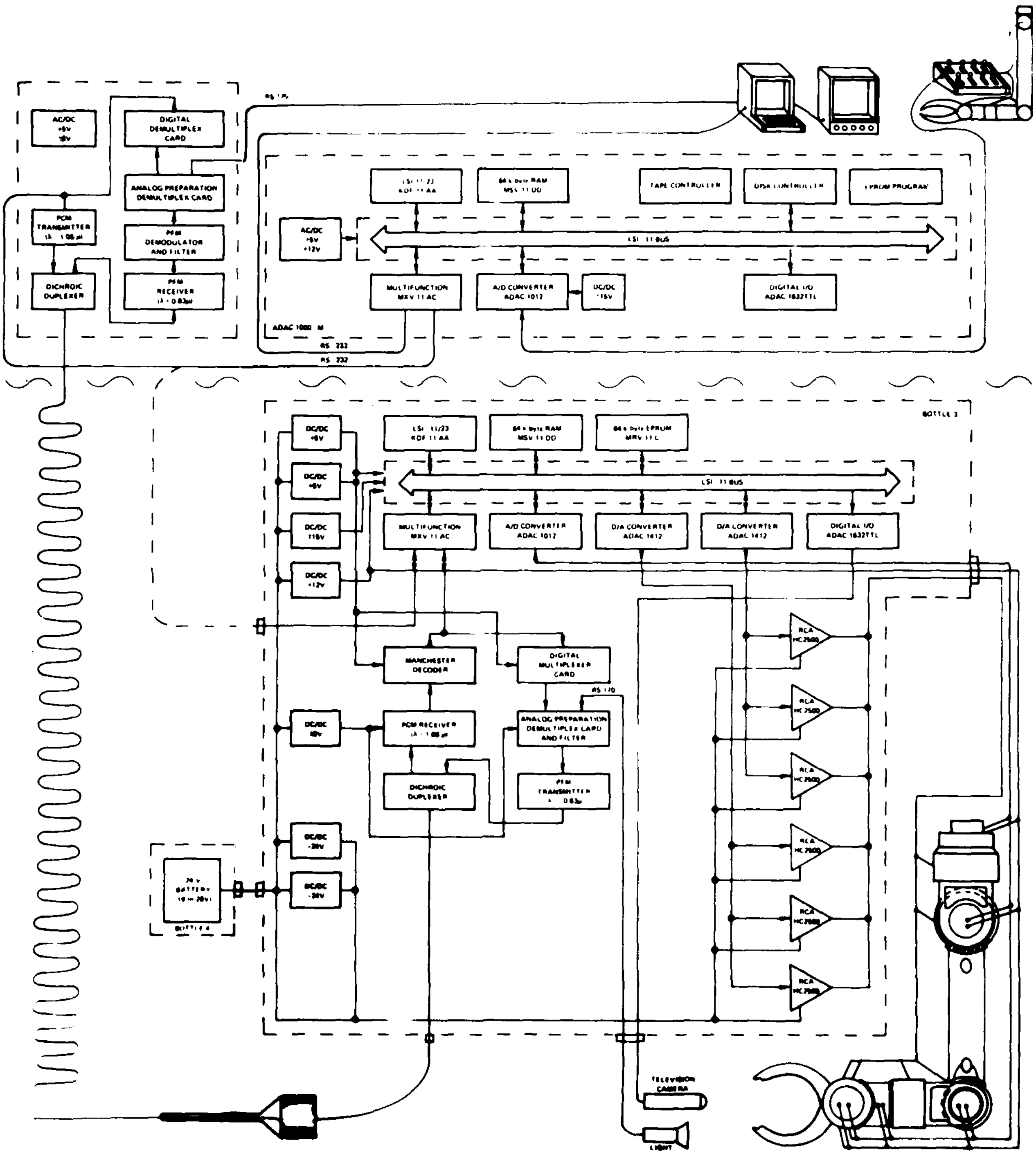


Figure 17. Supervisory-controlled manipulator.

Potential tasks involved for the manipulator relative to the USGS pipeline and structure inspection are as follows:

1. Positioning a cavitation, erosion-cleaning nozzle developed under contract to the USGS R&D program.

2. Placing a self-contained sensor package at selected positions on a structure; these packages may be attached either mechanically or magnetically.

3. Positioning imaging subsystems to allow visual inspection of welded joints and structural members; candidates include still and motion picture photography and conventional and solid-state television.

4. Attaching a line to instrument packages or navigation transponders through a hook arrangement to recover such packages from underwater structures or in the vicinity of pipelines on the ocean bottom.

Details of this work are in reference 13.

TEST RESULTS

Several in-water tests of the EAVE WEST testbed submersible were conducted during its development. Most of these tests, designed to validate the proper operation of various subsystem components and software control routines, were performed at NOSC's Transducer Calibration Facility (TRANSDEC) test pool, where the water was clear enough to allow easy visual and photographic observation of the vehicle's performance. Pool tests were also a protection against loss of the vehicle due to unexpected behavior, system malfunctions, or container flooding during its early stages of development. Tests were later performed in San Diego Bay off the NOSC pier. Although the water clarity and resulting visibility were poor, an idea of the vehicle's performance under more stringent conditions and in saltwater was obtained. Tests will eventually be performed at the NOSC San Clemente Island Facility, where performance of simulated inspection missions can be observed in relatively clear water (the optical volume attenuation coefficient is approximately 0.2/m).

INITIAL TESTS

Initial tests of the vehicle were performed at TRANSDEC in October 1978, while the vehicle was programmed to operate directly from a "dumb" ADM-3 terminal and was launched entirely in a preprogrammed trajectory mode. All console man/machine interaction programs and the vehicle's routines were stored in firmware within the vehicle's existing 8-bit 12 kilobytes of PROM memory. Only 2 kilobytes of RAM were required within the vehicle's memory to perform the scratchpad calculations to execute these programs. Most routines were originally written in Intel's 8080 microprocessor assembly language. There were no visual or data sensors on the vehicle at the time, and there was no real-time data or control communication link to the console subsequent to the vehicle's launch. The vehicle was simply preprogrammed to transit to the center of the pool area, execute a series of maneuvers, and return to the side of the pool. One of the significant features, however, was that it successfully performed these exercises using only a single small microprocessor (a total hardware cost of only $3000). An underwater photograph taken of the vehicle during this first operation is shown in figure 18. The results of these tests and a description of the status of the EAVE WEST submersible at the time are described in reference 14.

Accomplishments

During the first single-computer configuration test at TRANSDEC, the following results were achieved:

1. The vehicle was trim-ballasted according to theoretical calculations based upon estimated system component weight. The submersible was found to be 40 lb positively buoyant rather than the 86 lb previously calculated, which represented an error of less than 10 percent of the total vehicle weight.

Figure 18. Free-swimming vehicle during initial TRANSDEC tests.

2. The vehicle successfully executed various preprogrammed trajectories as modified by the operator. Each trajectory was found to be repeatable. The vehicle could even be made to return to the side of the tank and to stop when finished with a given run.

3. Data were obtained for the motor thrust and vehicle speed with respect to various programmed values.

4. Still and motion picture photographic coverage was taken of both the surface and subsurface runs.

5. The emergency and abort routines operated well.

6. The system was found to be relatively easy to transport, and it withstood moving with little difficulty.

Data Measurements

Forward thrust was measured to be an average of 38.5 lb when the vehicle was programmed for full speed.

Forward speed was measured by traversing a 60-ft timed run after the vehicle was up to speed. At full speed, the vehicle ran this distance in 19.5 s, indicating a maximum vehicle speed of 1.85 knots or 2.1 mi/hr. The speed was found to be independent of whether the vehicle was on the surface or submerged. These values are in excess of the maximum 1.5-knot speed predicted during the design phase.

Problems Encountered

Problems encountered with the system were minor. They are mentioned primarily to aid future designers of robot submersibles.

STATIC BALANCE. Because it was necessary to place all the batteries in one container to separate them from potential spark-producing electronics, the vehicle tended to list to one side. The problem was easily corrected during the trim and ballasting procedure by merely adding more weight to the other side of the vehicle to counteract the battery weight. Additional foam (figure 18) was also added to compensate for the resulting loss of buoyancy. These additional blocks of foam, however, probably increased the vehicle's drag in the water, resulting in a lower vehicle speed. In the future, as new electronic payloads are added to the submersible and more foam is added along the top corners of the frame, this problem is expected to disappear.

OPERATOR CONSOLE INTERACTION. Fast interaction with the terminal was a problem during the tests; too much time was wasted when it was necessary to reprogram the vehicle. Since that time, however, the trajectory design software has been upgraded not only to allow a selection of preprogrammed tracks, but also to allow development of new patterns based on keyboard input by the operator. In addition, this software has since been modified to accept a much faster operator interaction type of editing rather than the pure prompting-of-questions approach used during the TRANSDEC tests. Reprogramming now requires only 1 min rather than 5 min. Unfortunately, the disadvantage is that the operator must be a little more familiar with the program.

REAL-TIME CONTROL. The lack of real-time control during the TRANSDEC tests was not as serious a problem as expected, particularly since the surfaced vehicle experienced a definite water current caused by a relatively strong westerly wind. The current was rather constant, and it was observed that the vehicle could actually be programmed to return repeatedly to the side of the tank. However, in most circumstances, a lack of real-time control and some type of postlaunch reprogramming capability could either prevent recovery of the vehicle or cause the vehicle to be misdirected or lost.

SUPERVISORY CONTROL: FIBER-OPTIC DEVELOPMENT TESTS

During September 1979, another series of tests was performed with the vehicle to determine if the supervisory-control hardware and software architecture were functioning as designed and to study the dynamics of the fiber-optic link deployment. Again, the tests were performed in the TRANSDEC pool to aid visual and photographic observation and to protect against loss of the vehicle. Topside console programs used approximately 12 kilobytes of memory, and the major portions of the programs were updated to PLM. A television camera and light were mounted on the vehicle, but were not electrically connected or used. The fluxgate-updated gyro compass was used for this series of tests, replacing a magnetometer compass used during the initial tests. Most of the remaining electronic hardware stayed the same. A coffee can, nylon funnel, and 1/2-in PVC pipe were used as the fiber-optic deployment canister, which was temporarily strapped to the bottom of the vehicle's frame (see figure 19). Although deployment tests were performed, no actual fiber-optic communication link existed and there was no additional software to support real-time control of the vehicle.

Accomplishments

The two-processor, supervisory-controlled configuration operated without difficulty. There were no more problems encountered using this more complex structure than were observed during the initial tests with the single vehicle processor architecture. The more versatile trajectory design program, added to the console since the initial configuration, greatly enhanced the operator-to-console interaction speed.

The basic approach for deploying the optical-fiber link was validated, amd photographic coverage of the vehicle as it deployed the fiber-optic cable was obtained. Several runs were successfully made deploying unclad fiber, fiberglass-clad fiber, and dummy fiber (nylon line).

Problems Encountered

BATTERY LIFE. Although the use of lead-acid batteries is not a technological problem, much time was wasted because of the poor condition of some of the batteries. In general, the use of the parallel-series chain of the 2-V, 5-A-hr cells caused much of the problem. This eventually led to the adoption of a single-series chain of the more powerful 2-V, 25-A-hr cells.

MAN/MACHINE INTERFACE. Although much of the new software added to the console programs greatly enhanced the console-to-operator interaction speed, the man/machine interface problem remained an important consideration. It is very difficult in a short amount of time to communicate to a vehicle a-priori the

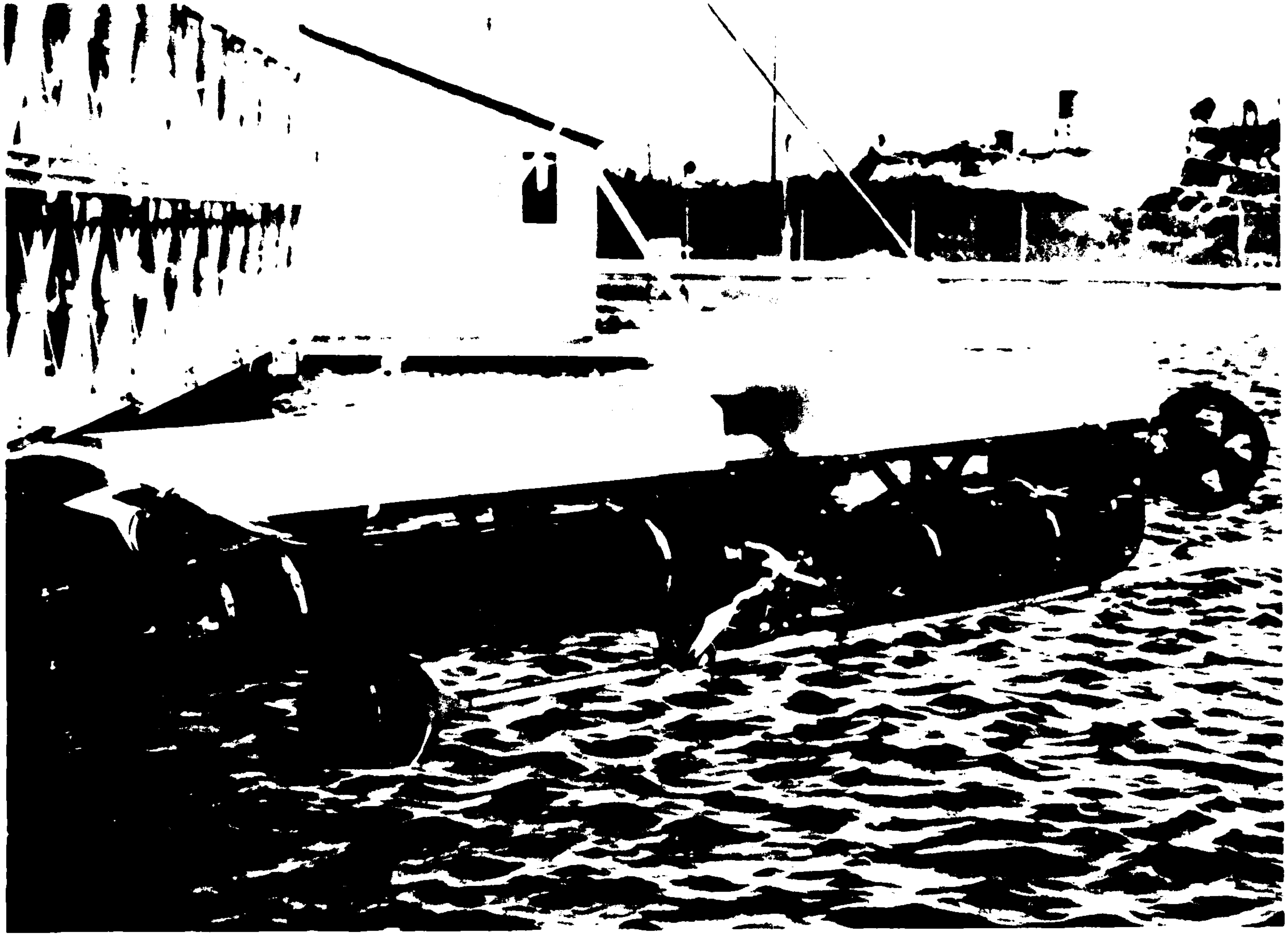


Figure 19. Fiber-optic deployment canister during supervisory control tests.

exact trajectory designed. The use of analogic controls and displays, such as graphics of the planned trajectory, analogic displays of panel meters, and joystick controls, greatly simplifies the procedure of operator interaction to the system. Symbolic displays, such as digital readings and digital depth indicators, require much time in the field to study and to understand their implications. The use of a computer keyboard is also somewhat limited for field test operations. The experience gained from this particular test, therefore, caused further investigation into the use of analogic controls and displays.

ENTANGLEMENT OF THE FIBER-OPTIC LINK. No problem was observed in deploying the fiber-optic link along a straight-line or forward-directed run. Difficulty was experienced on occasion, however, in deploying the more flimsy unclad fiber or the substitute nylon fishing line when performing simulated docking maneuvers. It was possible to entangle the link in the vehicle propellers when backing into the deployed cable. Although the link was held away from the thrusters by the deployment tube (or "stinger") hanging from the rear of the vehicle, this was proven to not be sufficient. Either a mechanical guard on the propellers or the more expensive, stiffer, fiberglass-clad fiber must be used. Further tests will have to be run.

REAL-TIME CONTROL TESTS

Tests on the ability of the vehicle to respond to real-time control commands were made in March 1980 at TRANSDEC and in San Diego Bay. The experiments were a preliminary step to the implementation of the projection mode of operation when the final fiber-optic link is installed. The cursor keys on the control console keyboard were used to control the direction and magnitude of the vehicle operated under proportional control. Hitting a given key once produced a 1/4 full thrust change in the control signals applied to the vehicle motors. Progress of the vehicle was visually monitored through an underwater television camera mounted on the vehicle when the vehicle was submerged. The vehicle was operated in the supervisory configuration with a minimum of top console display operator interaction. The console computer merely formatted and relayed the commands input from the keyboard to the vehicle. Vehicle response to the operator was the primary concern. A photograph of the entire operational set up as used during the TRANSDEC tests is shown in figure 6.

Accomplishments

During the TRANSDEC portion of the tests, experiments were devoted to operating the motor controls in a real-time mode using the television camera to guide and position the vehicle. These preliminary tests illustrated the following:

1. The vehicle operated without any mechanical or electrical failures.

2. The vehicle was controlled with real-time motor controls and performed the maneuvers necessary to submerge and follow the lip of the elliptical disk at TRANSDEC.

3. A good quality television image, received over the umbilical cable, was recorded on video tape.

4. Super 8-mm motion pictures were taken by the vehicle; they were activated remotely by the surface operator.

Similar results were obtained in the bay tests, except that visibility was poor and television and motion picture coverage of the ocean floor was limited accordingly. The controllability of the vehicle is amazing in that the vehicle is long and narrow and side drag prevents the use of differential thrust (reversing one motor) during turns. However, even with this limitation, a minimum turn radius of approximately 9 ft was observed.

Problems Encountered

Only minor problems were encountered, but they indicated the direction for improving the vehicle design which ultimately dictated the vehicle configuration described in the section on system description.

VEHICLE TRIM. Although two new 3-in battery bottles spanning the length of the vehicle had been designed, they were not yet fabricated and installed on the submersible at the time of these tests. Thus, the batteries again caused a bad list to one side of the vehicle. This caused an undue amount of delay in trimming the vehicle in the water. It took 16 lb attached to the forward starboard bottle and an additional 7 lb in the midsection of the vehicle on the starboard side to trim the vehicle. For the saltwater operation, the vehicle required an additional 12 lb attached to the center runner at the midsection of the vehicle. The vehicle trimmed out at about 1 lb positive buoyancy. Now that the new 3-in battery bottles have been fabricated and installed, the time required to trim the vehicle should be greatly reduced.

JOYSTICK CONTROLS. Direct control of the vehicle during this series of tests was achieved through operator interaction with the cursor controls and the "D" and "U" keys on the console keyboard. The use of these controls was a "quick and dirty" approach to operator interaction. A fair amount of concentration was required to remember which keys performed which function. This approach, therefore, has been replaced with two joystick controls mounted on each side of the console keyboard. The right-hand joystick controls continuous forward/reverse and right/left movements of the vehicle. The left-hand side dimensional stick provides proportional depth control to the vertical thruster. This approach has proven much more satisfactory in the laboratory and is now the new permanent means of analogic control of the vehicle when used in projection or real-time control modes.

CHARGING TIME. Much operational time was lost during these tests because of the time required to charge the batteries. A more modular approach has been adopted because of this experience. A set of extra battery bottles has been fabricated, allowing the operation to continue by changing the bottles in the field and recharging the first set while using the second set.

CONCLUSIONS AND RECOMMENDATIONS

The tests validated the achievement of the design goals discussed on pages 9 and 10 of this report. In addition, the tests indicated that the supervisory-controlled vehicle configuration allows a reliable, flexible software structure which provides a testbed for both projection and replacement of manned concepts. The modular software and hardware architecture concepts were not only realized, but they have helped finalize the designs which overcame problems encountered in the vehicle's development history.

Of the problems encountered during the testing phase, man/machine interaction stood out as an area which could always be improved. It was difficult in the field to visualize, communicate, and verify quickly the a-priori derived, data base information required to command the vehicle to execute a desired programmed trajectory. An editor-type program was required and augmented with a means of plotting the planned trajectory. Analogic displays were developed when possible to help the operator visualize the status of the operation at any given moment to aid real-time vehicle control in the field. This entire man/machine interface can be further improved in the future. Speed of interaction and ease of understanding the computer output information are the key areas for improvement. Similar man/machine improvements are foreseen as desirable as part of the manipulator package: A simulated master arm would allow analogic communication with the vehicle manipulator and special sensors and a moving cursor display would provide a means of keeping track of the manipulator claw through a low bandwidth communication channel. Such approaches are highly recommended in the design of future remotely or supervisory-controlled undersea vehicle systems.

Although the EAVE WEST testbed is far from being a truly autonomous undersea system, the approach taken to combine projection modes of operation with replacement (or autonomous) modes of operation has proven to have several advantages. First, advanced autonomous concepts are being approached one step at a time. Second, the operator can always "take over" when an autonomous operation experiences problems or is completed. Third, through experience, it is easy to identify primitive autonomous operations which would be useful even in undersea vehicles which are primarily operated as remotely controlled vehicle systems (RCVS) in projection mode. The eventual autonomous configuration might be configured from a hierarchy of such primitive operations.

It should be remembered that shape of the frame for the EAVE WEST vehicle can easily be changed to fit special requirements and missions. This is particularly important in commercial applications where it becomes quite cost effective to transfer the motors and electronic bottles to a new frame to achieve large differences in the performance of the vehicle in speed, maneuverability, or static stability. For example, it is possible to build a square or rectangularly shaped frame to make a much more stable platform for use with the manipulator configuration. On the other hand, speed could easily be traded for mechanical flexibility by packaging the entire pipeline inspection configuration into a cylindrical fairing using the fairing itself as the mechanical frame and gussets to hold the various bottles, sensors, and effectors. In either case, the present modular frame would simply be set aside.

The next step in the design of unmanned free-swimming submersibles should incorporate some more advanced form of artificial intelligence. As visual sensors are added to the EAVE WEST submersible, consideration should be given to the derivation of control information from these sensors by the vehicle computer. Scene analysis techniques or perhaps image processing of the video signal should help make this possible. The vehicle has proven itself to be a fairly reliable versatile testbed. It is easily adaptable to the test and evaluation of a wide variety of artificial intelligence concepts and it is recommended that work continue in this area.

REFERENCES

1. R. Frank Busby Associates, "Underwater Inspection/Testing/Monitoring of Offshore Structures," February 1979 (Commerce Contract 7-35336).

2. S. Y. Harmon, "Application of Robot Technology to the Marine Tactical Environment." June 1980 (in publication).

3. Naval Undersea Center, "Why Man?" Technical Note 953, by H. R. Talkington, February 1973.

4. Naval Undersea Center, "Manned and Remotely Operated Submersible Systems: a Comparison," Technical Publication 511, by H. R. Talkington.

5. R. A Geyer, "Submersibles and Their Use in Oceanography and Ocean Engineering," pp. 61-95, Elsevier Scientific Publishing Co: New York, 1977.

6. "Experimental Autonomous Vehicle Program EAVE; Development of Unmanned, Untethered Submersible Technology for Inspection Tasks," prepared for USGS Research and Development Program for Outer Continental Shelf Oil and Gas Operations.

7. D. R. Blidberg, E. E. Allmendinger, and N. Sideris, "The Development of an Unmanned, Self-Controlled, Free-Swimming Vehicle," Proceedings of the Offshore Technology Conference, 1978.

8. W. R. Ferrell and T. B. Sheridan, "Supervisory Control of Remote Manipulation," IEEE Spectrum, Volume 4, No. 10 pp. 81-88, October 1967.

9. S. J. Cowen, "Fiber-Optic Transmission System Pulse Frequency Modulation," Proceeding of Oceans 79, pp. 253-259, September 1979.

10. Naval Ocean Systems Center, "Fiber-Optic Communication Links for Unmanned Inspection Submersibles," by S. J. Cowen, M. Kono, and P. J. Heckman (technical report in publication).

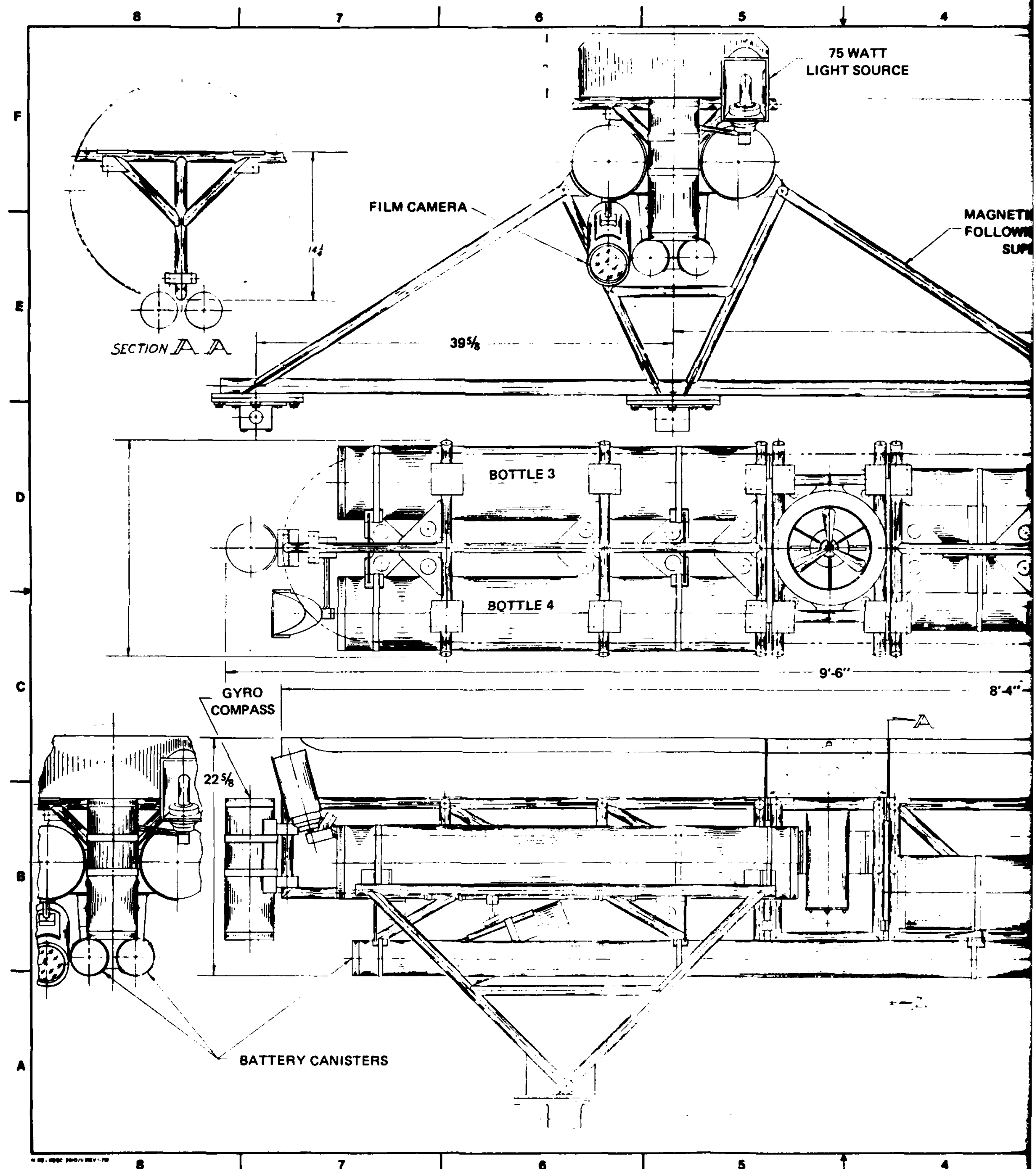
11. Naval Ocean Systems Center, "FY 77 Subsea Slow Scan Acoustic Television (SUBSAT) Tests," Technical Report 217, by A. Gordon, March 1978.

12. T. L. Brooks and T. B. Sheridan, "Experimental Evaluation of the Concept of Supervisory Manipulation," 16th Annual Conference on Manual Control, MIT Cambridge, Massachusetts, 5-7 May 1980.

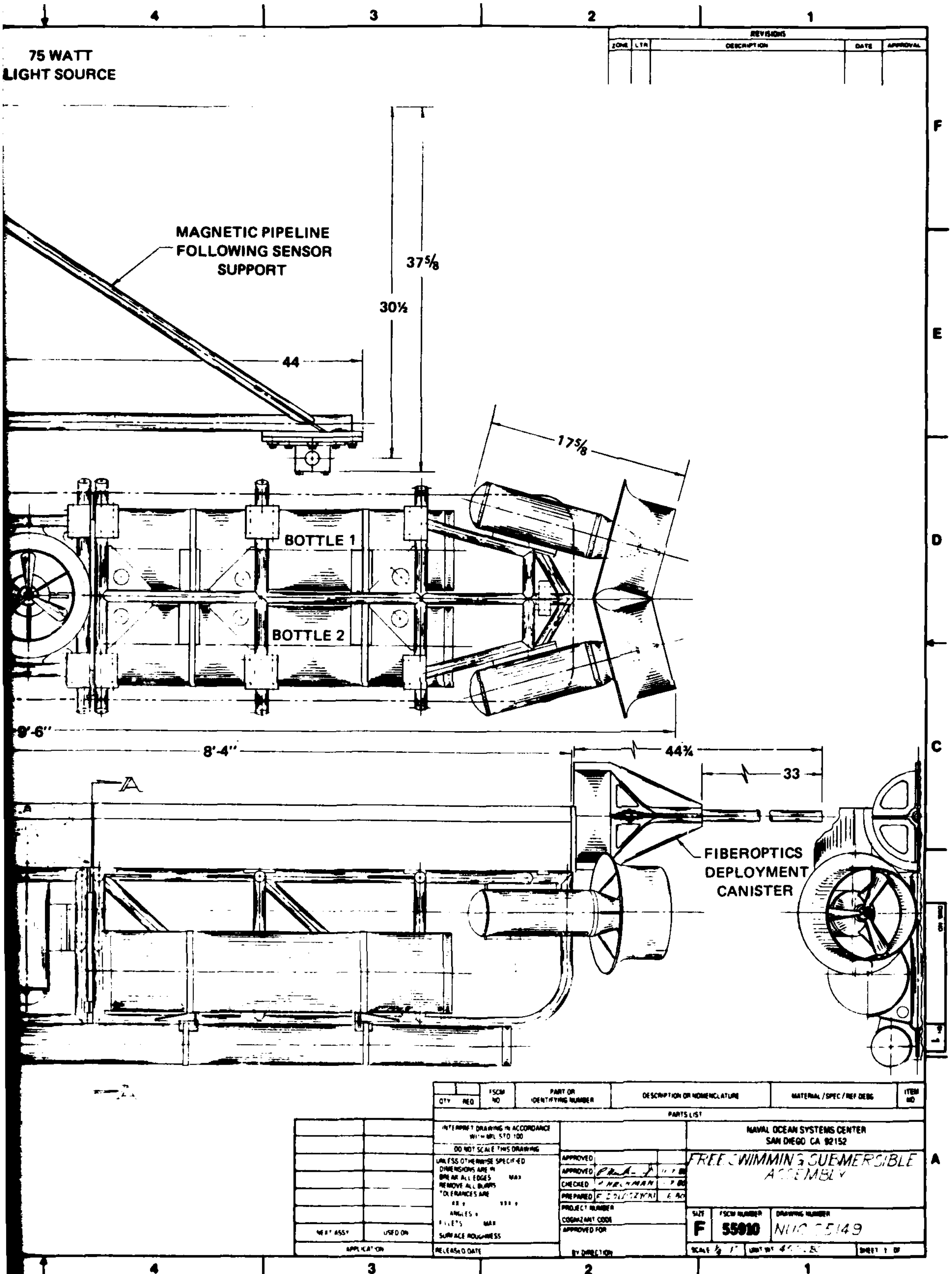
13. P. Heckman, D. Yoerger, T. B. Sheridan, "The NOSC/MIT Submersible Manipulator: an Experiment in Remote Supervisory Control of a Microprocessor Based Robot," Session FlOP on Robotics, International Conference on Cybernetics and Society, Cambridge, Massachusetts, 10 October 1980.

14. P. J. Heckman and H. B. McCracken, "An Untethered, Unmanned Submersible," Proceeding of Oceans 79, pp. 733-737, September 1979.

APPENDIX A: FREE-SWIMMING SUBMERSIBLE ASSEMBLY



PRECEDING PAGE BLANK-NOT FILMED


75 WATT
LIGHT SOURCE
MAGNETIC PIPELINE
FOLLOWING SENSOR
SUPPORT
37⅝
30½
44
17⅝
BOTTLE 1
BOTTLE 2
9'-6"
8'-4"
44¾
33
FIBEROPTICS
DEPLOYMENT
CANISTER
REVISIONS
PARTS LIST
NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO CA 92152
FREE SWIMMING SUBMERSIBLE
ASSEMBLY
F
55910

DA

FILM

4 -